Pennsylvania Climate Impact Assessment

Report to the Department of Environmental Protection

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1.0 Executive Summary

This report presents an assessment of the impacts of projected global climate change for Pennsylvania. This assessment was sponsored by the Pennsylvania Department of Environmental Protection (DEP) which, pursuant to the Pennsylvania Climate Change Act, Act 70 of 2008, is required to develop a report on the potential impacts of global climate change on Pennsylvania's climate, human health, the economy and the management of economic risk, forests, wildlife, fisheries, recreation, agriculture and tourism. Act 70 also requires DEP to report on opportunities, and barriers to their realization, created by the need for alternative sources of energy, climate-related technologies, services and strategies, carbon sequestration technologies, capture and utilization of fugitive greenhouse gas emissions, and other mitigation strategies. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) finds that "Warming of the climate system is unequivocal…" and that "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases." The report also finds that "A global assessment of data since 1970 has shown it is likely that anthropogenic warming has had a discernible influence on many physical and biological systems."

Most of the sectors considered in this report were explicitly mandated by Act 70 of 2008. Other sectors were added in consultation with DEP and recommendations from the Climate Change Advisory Committee (CCAC). Criteria for selecting additional sectors, and that guided the depth with which all sectors are examined included: (1) the importance of the sector to the state's economic and social wellbeing, and ecological health; (2) the expected sensitivity of the sector to climate variability and change; and (3) the data and scientific results available to perform a credible assessment given the resources available for this study. The sectors are agriculture, ecosystems, energy, fisheries, forests, human health, insurance, outdoor recreation, tourism, water, wildlife, and the general economy.

Ideally, the impact of projected climate change on any given sector is assessed using a mixture of approaches, including integrated quantitative modeling of the sector and extensive stakeholder engagement. The findings are based on readily available data, literature, and some preliminary quantitative analyses. A more in depth analysis would require significantly more time for compilation and analysis of new data. It is important to note in this context that there is limited scientific literature addressing the impacts of projected climate change in Pennsylvania. In consequence, this assessment largely interprets the implications for Pennsylvania of scientific literature that applies broadly and from which we can reasonably infer impacts in Pennsylvania. Such inferences make extensive use of relevant contextual data and information for Pennsylvania, and as is the case throughout this report, indicate the level of confidence in the conclusions.

1.1 Pennsylvania's Climate Futures

General Circulation Models (GCM) have become useful tools for projecting the climate impacts of greenhouse gas emissions. We conducted an assessment of the reliability of a suite of GCMs for the climate averaged over the Commonwealth. Our overall findings using a variety of metrics based on surface temperature and precipitation are:

- Individual GCMs differ dramatically in their ability to simulate the climate of Pennsylvania;
- The multi-model mean produced a credible simulation of Pennsylvania's recent climate, superior to the simulation of any individual GCM; and
- The multi-model mean is slightly too cool and wet, and is slightly muted in its variability on sub-monthly time scales.

The credible simulation of Pennsylvania's past climate found in this evaluation implies that GCM projections for the region can provide useful information for the impacts of projected climate change. The spread across results from individual GCMs provides a rough estimate of the GCM error. Two plausible IPCC global emissions scenarios are used for our analysis of Pennsylvania's climate future. One scenario assumes continued growth in global emissions throughout the 21st century. This "high" emission scenario is the A2 scenario of the IPCC Special Report on Emission Scenarios (SRES). The second, lower emissions scenario, assumes global emission's growth is moderated to the middle of the 21st century and declines thereafter. This scenario is the IPCC SRES B1 scenario. Our main findings for the projected climate of the Commonwealth are:

- It is very likely that Pennsylvania will warm throughout the 21st century; not a single GCM simulates cooling under the high (A2) or low (B1) emissions scenarios.
- It is likely that annual precipitation will increase in Pennsylvania and very likely that winter precipitation will increase in both emissions scenarios.
- Projected climate change for the Commonwealth over the next 20 years does not differ between the high and low emissions scenarios. Pennsylvania's projected climate by the end of the century differs significant between the two scenarios. .
- By the end of the century, the median projected warming according to the A2 scenario is almost 4 degrees C (7 degrees F), which is nearly twice that of the B1 scenario.
- By late century, the median B1 and A2 annual precipitation projections increase by six and 10 percent, respectively. Corresponding winter projections are eight and 15 percent.
- Warming will lead to a longer growing season, with median B1 and A2 projections of nearly three and five weeks lengthening, respectively, by late century. Corresponding frost day decreases are nearly four and six weeks.
- It is likely that Pennsylvania's precipitation climate will become more extreme in the future, with longer dry periods and greater intensity of precipitation when it occurs.
- There is substantial uncertainty in projections of future tropical and extratropical cyclones for Pennsylvania. Current research suggests fewer storms but with increases in intensity.

1.2 Water Resources

Precipitation is projected to increase in winter and generally follow current patterns or increase slightly in the summer. Conclusions regarding the future of Pennsylvania water resources are mainly based on changes to atmospheric moisture and energy availability. Heavy precipitation events are also projected to increase. At the same time temperature is projected to increase relatively evenly throughout the year.

One consequence of this change would be a significant decrease in snow cover extent and duration throughout Pennsylvania. More precipitation would fall as rain, rather than as snow. Increasing temperature is likely to lead to increasing evapotranspiration (the combined amount of water moving into the atmosphere from evaporation from the earth's surface and from transpiration from plants). Since summer precipitation and evapotranspiration are already about equal, it is likely that we will see an increase in soil moisture related droughts throughout late spring to early fall. The frequency of short and medium length soil moisture droughts is thus projected to increase. On the other hand, groundwater recharge could increase due to fewer days with frozen ground and more precipitation during the winter time when evaporation is low and plants are not active. Summer floods and general stream flow variability are projected to increase. A reduced snowpack might cause a reduction in rain-on-snow events, a process which historically caused major flooding events in Pennsylvania, though this conclusion remains speculative before more detailed studies have been performed.

Overall, Pennsylvania is likely to see a small increase in runoff in the order of five to 10 percent. However, this increase will basically all be during the winter months while summer flows might actually be reduced. The interaction with changes to groundwater recharge and the potential for more baseflow is less clear at this time. Stream temperature, an important water quality characteristic for aquatic ecosystems, is likely to increase thus potentially causing problems for species which require cold water for at least part of their life cycle. This increase in water temperature in combination with flashier runoff due to more extreme precipitation and due to increased urbanization would negatively impact Pennsylvania water quality and potential impair estuaries into which the river network drains. At the same time, higher sea levels would increase salt water intrusion in coastal waters.

1.3 Forests and Wildlife

Climate change will likely cause many changes in Pennsylvania's forests. First, the state will become increasingly unsuitable for many of the tree species that are now present, especially those generally associated with northern hardwood ecosystems. Northern species such as paper birch, quaking aspen, bigtooth aspen, and yellow birch are projected to be extinct in the state under high emissions scenarios, and greatly reduced, if not eliminated, even under low emissions scenarios. Other species, including American beech, black cherry, striped maple, eastern hemlock, red maple, sugar maple, eastern white pine, sweet birch, white ash, and American basswood, are projected to find

increasingly less suitable habitat in the state and will likely decline in numbers. In general, the state is projected to become increasingly hospitable for more southern species such as oaks and hickories, although the state's two most common oaks, northern red oak, and chestnut oak, are projected to decline under high-emissions scenarios. The state will also become increasingly suitable for some species that are currently rare or not present in the state, such as loblolly and shortleaf pines, common persimmon and red mulberry, although it is not clear how these species will come to the state without human intervention.

The warming climate will cause susceptible species to become increasingly stressed. Their mortality rates will increase and their regeneration success will decline, resulting in declining populations in the state of those species. The increasing stress due to climate change will also make some species more susceptible to a host of other stressors, including acid deposition and both native and non-native insects and diseases. Tree mortality could rise due to these secondary impacts, and it may be difficult to attribute these changes directly to a changing climate. Tree mortality could also increase if climate change increases the frequency of severe storms, and fires may become more common as temperatures rise.

Some studies suggest that a longer growing season, warmer temperatures, possibly higher rainfall, and a phenomenon termed "CO_2 fertilization" may increase overall forest growth rates in the state. However, these effects may likely be offset by increased mortality rates, at least until the climate stabilizes and the mix of tree species in the state is once again in a more stable equilibrium with the state's climate.

The state's forest products industry will need to adjust to the changing resource, but humans and their activities tend to be more adaptable than ecosystems. The industry could benefit from planting faster-growing species and from salvaging dying stands of trees. On the other hand, if mortality is dramatic and sudden, as might occur with an extended drought or a major storm such as a hurricane, the industry might not be able to utilize all of the dead wood. Substantial investments in artificial regeneration may be needed if large areas of forests begin to die back due to climate-related stress.

Forests can contribute to the mitigation of climate change by sequestering carbon. While it may be difficult to substantially increase the growth rates of Pennsylvania hardwoods, additional carbon can be sequestered and stored in the state's forests by increasing stocking levels or reducing stocking reductions, especially those due to poor management practices such as high-grading (a harvesting technique that removes only the biggest and most valuable trees from a stand) and diameter limit cutting (a harvesting technique that removes trees over a specific diameter regardless of the species, age, quality, or vigor). Marginal lands, such as abandoned mine lands can be reforested, but, again, the best opportunities may lie in preventing forest loss, rather than increasing the number of forested acres. Since 70 percent of Pennsylvania's forests are privately owned, often in small, family-owned parcels, it will be necessary to engage private forest landowners if significant changes are to be made in how Pennsylvania's forests are managed. Forests can also be a significant source of biomass for either direct burning or conversion to

biofuels. Biomass is the only currently viable alternative to fossil fuels for producing liquid fuels, and biomass production does not directly compete with food production.

There is little doubt that Pennsylvania's forest ecosystems are going to be affected by climate change in the coming decades. However, there is much that can be done to adapt to these changes. They include:

- Managing for healthy, resilient forests with a high degree of biodiversity.
- Research to better predict the impacts of climate change on the forests in the Commonwealth.
- Monitoring the health and productivity of the forest resource to identify and detect the effects of climate change.
- Recognizing potential climate-change induced stresses when planning forest management activities.

Most of these strategies will provide benefits regardless of how dramatically the state's climate changes.

1.4 Aquatic Ecosystems and Fisheries

Existing aquatic ecosystems and fisheries in Pennsylvania are expected to be stressed by projected climate changes. The most significant effects predicted for stream and wetland communities are increased water temperature and increased variability of the water environment. The latter may be reflected in changing seasonal patterns of water levels, reduced stream flows during dry periods, larger floods and longer droughts. Wetlands and headwater streams in Pennsylvania are already compromised in their ability to provide ecosystem services, due to degraded conditions resulting from modification of hydrology and nutrient enrichment. These stressors primarily arise from human activities associated with agriculture and development.

Such changes in temperature, water quantity and water quality will most certainly affect stream and wetland biological communities, and the largest negative impact may be in lost biodiversity. Pennsylvania may see a decline in some of our most valued coldwater communities and a simultaneous increase in the abundance of less desirable biological assemblages (groups of ecologically related organisms that are part of an aquatic community), especially invasive species. Of special concern is the impact of higher temperatures and altered flow regimes on Eastern Brook Trout, not only because of its status as a recreationally and culturally important species, but because it is an indicator of high water quality and may be an early victim of deletrious impacts of climate change. Eastern Brook Trout will continue to decline as a result of higher water temperatures. Wetlands may experience a similar change in habitat conditions, as hydrologic variability changes habitat structure. Potential impacts on other valued ecosystem services of streams and wetlands (e.g., carbon sequestration, nutrient removal, flood storage) cannot be predicted at this time. Impacts of climate change on aquatic ecosystems will be difficult to detect because of the continuation of primary stressors to their condition such as development and invasive species.

At a larger spatial scale, climate change is likely to alter the chemical, physical, geological, and biological processes and reactions that govern the composition of the aquatic environment of the Chesapeake watershed via the large contribution of the Susquehanna River to its total freshwater input (51 percent). The direction of change is not well constrained given the uncertainty in flow projections, as well as the lack of a mechanistic understanding of watershed processes. Nutrient and sediment loading during winter and spring will likely rise due to the anticipated increase in flow during this time, due to increased run-off and erosion of stream banks.

Current research suggests that ecologically-relevant hydrologic responses to precipitation and temperature will vary over the spatial scale of a small watershed, making spatially-explicit predictions difficult. However, the general pattern appears to be towards a slightly wetter scenario, which may result in an expansion of wetland area and an seasonal increase in stream discharge. However, changes in hydrological factors such as flow amount, timing, and frequency are significant variables in structuring plant and animal assemblages; alterations in the hydrology could greatly modify assemblage structure for plant, macroinvertebrate, amphibian, and fish communities.

Strategies to avoid the above impacts from climate change need to center around maintaining and improving the resiliency of aquatic systems through minimization of nutrient enrichment, hydrologic modification, habitat fragmentation and degradation, and species loss. Such actions would include:

- Protection of existing stream and wetland habitat, especially intact habitat for identified species of interest, such as Eastern Brook Trout
- Consideration of hydrological connectivity within and between stream and wetland habitats;
- Maintenance of riparian forests for moderation of stream temperature and treatment of run-off from adjoining lands;
- Implementation of Best Management Practices to reduce nutrient loading;
- Restoration of aquatic ecosystems such as streams and wetlands wherever possible; and
- Minimize groundwater pumping for irrigation, human consumption, etc., that removes water from aquatic ecosystems

1.5 Agriculture

Moderate climate change on the order of 1-3 degrees C (2-5 degrees F) may raise Pennsylvania yields of hay, corn, and soybeans, but it may also raise yields elsewhere in the U.S. and around the world, increasing global production and pushing down prices received by Pennsylvania farmers. Greater climate change could lower Pennsylvania yields of these crops, but it could also lower yields elsewhere, reducing global production and raising prices received by Pennsylvania farmers. In either case the net effect on Pennsylvania farm revenues for these crops is likely to be small.

Yields of cool-temperature adapted fruits and vegetables such as potatoes and apples are likely to decline as a result of climate change, while yields of fruits and vegetables better suited to a warmer climate such as sweet corn are likely to rise. Pennsylvania farmers are likely to adapt to climate change by changing the types and varieties of fruits and vegetables grown. Pennsylvania wineries may choose to replace some of their native American grape varieties with higher-value European varieties.

The effects of climate change on Pennsylvania livestock producers are likely to be mixed. In the dairy industry, heat stress with increased temperatures and a possible decline in the quality of pastures with changes in temperature, precipitation, and atmospheric CO_2 are likely to drive milk yields downward and increase production costs. For operations that rely on grazing and on-farm production such as dairy and beef herds, changes in pasture yields and feed quality will impact production costs. At moderate levels of warming, this effect is likely to be positive; however, higher temperature rise will probably have a negative impact. For the state's hog and poultry producers, while climate control costs are likely to increase with warmer summer months, this same effect in southern states may make Pennsylvania more attractive to these industries and could induce a northward shift in production operations.

Among Pennsylvania farmers, dairy producers may experience the greatest challenges from climate change given their reliance on own-crop production, animal heat stress due to housing in the ambient environment, and impacts to forage quality that will affect productivity. If future global trade agreements lower U.S. tariffs on dairy products, dairy producers in Pennsylvania will also be facing greater competition from New Zealand, Australia, and Argentina. The existence of productive and profitable dairy industries in states to the south of Pennsylvania suggests that Pennsylvania dairy farmers can adjust to a warmer climate, but they will likely need to enhance the efficiency of their operations to offset climate change impacts. Dairy farms in southern states today tend to have larger herd sizes than Pennsylvania dairy farms, allowing them to take greater advantage of economies of scale.

1.6 Energy

Continued warming of Pennsylvania's climate is very likely to increase the role that energy plays in the Commonwealth's economy, as warmer summers lead businesses and individuals to increase the use of air conditioning for indoor climate control. The role of a reliable and affordable supply of electricity will increase in importance for Pennsylvania, particularly under high electric demand growth scenarios or scenarios where transportation becomes electrified to a large degree. Perhaps most importantly, peak electricity demand in Pennsylvania will likely grow at a faster rate than average demand. Peak electricity demand is expensive to serve, since it requires building and utilizing low-efficiency generators that only operate a limited number of hours per year. Growth in peak demand also introduces additional challenges in maintaining electric reliability.

The choice of technologies and policies for meeting increased electricity demand and eventually replacing the existing fossil-fired generation fleet will play a significant role in

how greenhouse gas emissions can be controlled in Pennsylvania, and the extent of any mitigation opportunities. Pennsylvania's Alternative Energy Portfolio Standards (AEPS) and demand-reduction targets under Act 129 represent a first step, but a number of opportunities for increased energy efficiency and peak demand reduction remain. The Commonwealth should focus on those areas with the highest potential returns – electricity demand reduction and a significant increase in customer self-generation, cogeneration and energy-efficient space conditioning.

Pennsylvania is among several states investigating a low carbon fuel standard (assuming that carbon intensity of electricity generation can be appropriately reduced), which is an effort to decrease the average carbon intensity of transportation fuels. Two technology options include greater reliance of electricity and increased utilization of compressed natural gas (CNG) for transportation.

Electrification of transportation, particularly urban and suburban transportation, holds significant promise for decreasing greenhouse gas emissions from the transportation sector, serving as distributed storage devices for absorbing variability in wind and solar power output, and potentially for meeting localized peak electricity demands. On a per-mile basis, the average emissions profile for electricity generation represents a net reduction in carbon intensity as compared to the use of petroleum-based transportation fuels. If electric vehicle propulsion becomes more common place, a clear opportunity is created to meet this demand through carbon-free or carbon-sequestered electricity.

Natural gas, because of its lower carbon intensity as compared to other fossil fuels, can play a role in reducing greenhouse gas emissions from the transportation sector through increased utilization of CNG for vehicle fleets. Development of the Marcellus Shale gas formation represents a major potential supply source and economic opportunity for both Pennsylvania and the U.S. Northeast. Increasing market share of natural gas for electricity generation, heating and transportation can provide reductions in greenhouse gas emissions.

Emissions reduction opportunities in the electric power sector exist through increased use of natural gas-fired combined heat and power (CHP), where waste heat from the power generation process is used in industrial processes or to heat water. It is important to realize that since PJM is a regionally integrated electricity market, the use of cost-effective CHP generation can not only reduce emissions, but lowers costs for all users on the system since the construction of new generation, transmission and distribution facilities is avoided. There is also exists some evidence of a shift towards natural gas generation and away from coal for base-load generation, due in part to factors related to electricity deregulation and in part to uncertainty over future environmental regulations. The generation interconnection queue for PJM shows that approximately two-thirds of proposed new power plants in Pennsylvania will be fueled by natural gas.

Pennsylvania faces significant opportunities in the area of long-term geologic carbon sequestration. The sequestration assessment and risk assessment required as a part of Act

129 should serve as the starting point for a legal, regulatory and economic assessment of sequestration within the Commonwealth.

1.7 Human Health

Year-round increases in temperature will have several impacts on human health. Increased summer heat will cause more heat-related deaths. The direction of this impact is established with high confidence. However, as residents install and increase use of air conditioning, the population will become less vulnerable to extreme heat. This adaptation has already occurred in southern U.S. cities, and is expected to occur in Pennsylvania as well. A negative side effect of this adaptation is that increase air conditioning installation and use will increase energy demand, particularly during peak demand periods. While most Pennsylvania residents will adapt to rising temperatures with installation and greater use of air conditioning, residents with limited resources will be unable to afford to install or operate air conditioning. Measures to minimize heat-related mortality should be targeted to these vulnerable populations. These measures could include programs to subsidize installation of air conditioning. Warning and outreach programs such as Philadelphia's Hot Weather-Health Watch/Warning System have already proven themselves to reduce heat-related mortality.

Increased winter temperatures will mean fewer cold-related deaths. The direction of this impact is also established with high confidence. It is difficult to project which effect will dominate, but there is some evidence that the reduction in cold-related deaths will be larger than the increase in heat-related deaths.

Increased summer temperatures will result in increased formation of ground level ozone. The direction of this impact is established with high confidence. Increased ozone concentrations have been shown to be related to higher incidence of respiratory disease and death. Individual households have few opportunities to self-protect from increased smog in the summertime, though air conditioning does provide some protection by allowing people to stay indoors during periods with poor air quality. The most important adaptation that could be made to reduce summer smog formation is a reduction in the emissions of VOCs and nitrogen oxides. A second adaptation that would reduce both heat-related mortality and summertime smog formation would be to take actions to decrease urban heat island effects. Adaptations include use of paving materials that absorb less heat, reflective roof coatings, and increasing tree and vegetative cover.

Increased summer temperatures may also result in higher concentrations of particulates, though the direction of this impact is established with low confidence. Higher particulate concentrations have been shown to be related to higher incidence of respiratory and heart disease. Similarly, higher summer temperatures and higher CO2 concentrations may result in higher concentrations of airborne allergens such as mold spores and pollen. The direction of this impact is also established with only low confidence.

Deaths and injuries from severe weather events such as floods and winter storms are not expected to change significantly as a consequence of climate change. While winter

precipitation is expected to increase, because snow depth and coverage will decrease, there will be fewer rain-on-snow flood events. There may be an increase in summer floods due to increased variability in precipitation. As for winter storms, there will be fewer winter snowstorms and more winter rainstorms. The frequency of ice storms may decrease, but the direction of that impact is established with low confidence. Even if Pennsylvania were to experience more ice storms that would not necessarily imply higher traffic casualties. Death rates during ice storms are actually lower than during dry weather, due to adjustments made by drivers.

It is not clear whether vector-borne diseases such as Lyme Disease and West Nile Disease will become more prevalent in Pennsylvania as a result of climate change. Continued disease monitoring is important. However, warmer temperatures would lengthen the season during which the vectors that carry these diseases are active, increasing potential exposure. Further, warmer temperatures will likely result in people spending more time outdoors for a longer portion of the year, also increasing exposure. Public education about actions that can be taken to minimize the risk of infection will be an important tool to limit the potential increase in disease associated with increased exposure.

Increased precipitation will likely increase runoff that caries infectious pathogens, so that the risk of water-borne disease will increase. The direction of this impact is established with medium confidence. For most Pennsylvania residents, drinking water is well protected by treatment systems. A properly designed and well maintained public water system should be able to handle increased pathogen loads in source water without endangering public health. The more likely pathway for exposure is direct contact with surface water. With increased temperatures, water-based recreation is expected to increase, so that exposure to water-based disease will increase. Actions should be taken to reduce pathogen loads to streams and lakes from agricultural and human sources, to monitor bathing water quality at popular bathing sites, and to educate users on ways to minimize the risk of disease from contact with surface water.

It is difficult to predict what impact climate change might have on incidence of air-borne infectious disease. While air-borne diseases like influenza show a clear seasonal pattern that does not necessarily mean that changes in climate will change the overall, yearlong disease burden.

1.8 Tourism and Outdoor Recreation

Changes in the Pennsylvania climate will have negative impacts for some activities (notably winter sports and trout fishing) and positive impacts for other activities (warm-water fishing, swimming and boating, golf, and outdoor exercise). Adaptation options include those aimed at minimizing negative impacts and those aimed at capitalizing on new opportunities.

The outdoor recreation activities that will be most severely impacted are snow- and ice-based recreation such as skiing, snowmobiling and ice skating and fishing. There is very

high confidence in the direction of these impacts. Downhill ski resorts can partially adapt to higher temperatures by increasing their use of snowmaking during the (now shorter) cold periods. Newer snowmaking equipment is more efficient and can make snow at slightly warmer temperatures. Increased snowmaking is expensive and uses energy, however. Projections for Pennsylvania are that, even with increased snowmaking, ski season length under the B2 emissions scenario will decrease by 29 percent in western Pennsylvania and by 32percent in eastern Pennsylvania by the end of the century. Under a higher emissions scenario (the IPCC A1Fi scenario) the decreases in season length are larger, from 46-50 percent respectively. It is questionable whether resorts would be economically viable with such short seasons.

Dispersed snow-based recreation such as cross country skiing and snowmobiling are at even more risk. Pennsylvania's climate is already marginal for these activities. As a consequence of warming and less snowfall, the number of days when conditions are suitable for cross country skiing or snowmobiling in Pennsylvania is projected to decrease under the B2 scenario by 61 percent in north-central Pennsylvania and by 75 percent in eastern Pennsylvania by the end of the century. Under the higher A1Fi emissions scenario, the season length is projected to decrease by 89 percent in both regions. Because snowmaking is not practical, there are few adaptation opportunities for these activities.

Increased temperatures will reduce the number of stream stretches that can support wild trout populations. The direction of this impact is established with high confidence, though the magnitude of the impact is uncertain. Increased stocking can serve as a partial substitute for lost wild trout habitat, but some waters will become too warm to support even stocked trout. A reduction in the availability of cold-water fishing does not mean that fishing activity will decline, however. In fact, the evidence is that total demand for fishing days will most likely increase, due to a longer season with pleasant weather and due to a desire to be near water on hot days. The direction of this impact is established with medium confidence. The Fish and Boat Commission should consider this possible increase in warm-water fishing activity when planning its programs to provide anglers access to streams and lakes.

It is difficult to project whether climate change will have either a positive or a negative impact on hunting participation. The most important game species in Pennsylvania are fairly widely distributed, and tolerant of different climates. Changes in forest composition could affect wildlife abundance, but the direction the impact is difficult to predict. Similarly, changes in weather could affect hunter behavior, but again the direction of the impact is difficult to predict. Likewise, participation in non-consumptive forest-based recreation such as hiking and camping could be affected by climate change. Higher temperatures will lengthen the season for such activities, but could make them less enjoyable in the middle of summer. Changes in forest composition could also affect these activities. The direction that climate change might impact these activities cannot be established.

Warmer summer temperatures and a longer summer season will increase demand for water-based recreation other than fishing, such as swimming and boating. There is high confidence in the direction of this impact. The state could capitalize on this increased demand by providing more opportunities for water-based recreation in the form of new stream access points and reservoirs

Finally, a longer warm season will encourage residents to spend more time in outdoor sporting and exercise activities such as golf, tennis and biking. There is high confidence in the direction of this impact. For example, studies have consistently shown that golf participation is positively related with temperature, due mostly to a longer golfing season. The same effect would be expected for other outdoor sports. Local communities should plan for this increase in demand for sports fields, bicycle paths, etc.

1.9 Insurance and Economic Risk

Though climate change carries the potential to exacerbate the risks of weather-related losses for the insurance industry, Pennsylvania's insurers are less exposed to such risks than insurers in other states. The available evidence does not permit us to say anything definitive about the effects of climate change on hurricane and flood risks. Ice storms and freezing rain may become less prevalent in the fall and spring, but it is unclear whether such events will be more or less prevalent during the winter. Pennsylvania may be at increased risk for wildfires, but it is unclear as to how large the increase in risk will be.

Effective regulatory management of the insurance industry that fosters competition will continue to protect Pennsylvania's citizens from insurer insolvency. Pricing insurance products in line with risk is also important for solvency, and can create incentives for beneficial adaptation to climate change. Accordingly, insurers should continue to price policies according to risk, and they should remain vigilant in evaluating how their risks may change with climate change. Insurers should collaborate with climate scientists and make efforts to integrate climate change into their pricing decisions. Insurers should also educate policyholders about how climate change might affect the risks facing them. Other adaptation options include land use regulation and decision-making with climate change in mind, improved building codes, reinsurance, and other risk-spreading financial instruments.

Insurance companies should be aware of opportunities to combine environmentally friendly practices with reduced loss exposures. Such mitigation activities include rate reductions for green products and insurance products for the alternative energy industry. It is vital that the stakeholders in Pennsylvania's insurance industry act and adapt to climate change while recognizing the significant uncertainties surrounding this issue. As knowledge about climate change improves, the insurance industry in Pennsylvania will need to adapt to ensure its future vitality. Similarly, with respect to health and life insurance risks, the potential impacts of climate change on human health are not fully known or understood.

1.10 Economic Barriers and Opportunities for Pennsylvania

Opportunities for adaptation to climate change in Pennsylvania, and also related to climate change mitigation in Pennsylvania are numerous. Some of these opportunities are *economic*, and hold the potential to create new jobs or industries in Pennsylvania. Others are *policy-oriented*, focusing largely on roles that the state could play in the climate-related adaptation or mitigation efforts of certain sectors of Pennsylvania's population, environment and economy. Sector-specific opportunities related to mitigation or adaptation are described in the chapters throughout this report. Section 14 provides a summary of the opportunities and barriers.

Table 1.1 provides a summary of the opportunities identified throughout the report. We have broadly classified economic opportunities related to mitigation or adaptation as either being *policy-driven* or *driven by the impacts of climate change*. Policy-driven opportunities hold significant promise for the Commonwealth, but are unlikely to arise without appropriate policy measures in place. In many cases, policy-driven opportunities address mitigation of Pennsylvania's greenhouse gas emissions, and the policies required to take advantage of these opportunities will need to be put in place soon. Climate change-driven opportunities are largely more adaptive in nature, and address ways in which various sectors of the Commonwealth's economy can adjust to a warmer Pennsylvania climate. While these opportunities will generally not be available to economic sectors in Pennsylvania until the Commonwealth sees significant climate change, many require additional research or planning that needs to begin soon.

Opportunities Driven by Climate Policy	Opportunities Driven by Climate Change
1. A CO_2 Sequestration Services Sector:	*1. New Risk-Management Products:*
- Geologic	- Agricultural
- Terrestrial (Agricultural)	- Consumer, Commercial and Residential
- Forests	*2. Warm-Weather Outdoor Recreation*
2. Managing Peak Electricity Demand	*3. New Agricultural Products*
3. Reducing Overall Energy Consumption:	*4. New Forestry Products and Practices*
- Energy Efficiency	*5. Maintaining Ecosystem Services and Freshwater Services*
- Self-generation and Co-generation	
4. Renewable Energy Development	
5. Alternative Transportation Fuels:	
- Electrified Transportation	
- Low-Carbon Biofuels	
6. Agricultural GHG Mitigation	

Table 1.1. Economic opportunities related to climate change in Pennsylvania.

The opportunities identified Table 1.1 are not all mutually exclusive. Significant synergies may exist between opportunities or between sectors. Clear examples of cross-sector synergies might include:

- Terrestrial sequestration in Pennsylvania's agricultural lands and changes in agricultural practices through conservation tilling;
- Renewable energy development and a transition to electrified transportation;
- Maintaining ecosystem services and increased opportunities for warm-weather outdoor recreation in Pennsylvania.

In addition, the aggressive development of some opportunities may hamper the development of other opportunities. Some opportunities may simply disappear, or may become less beneficial. Examples might include:

- Reducing overall energy consumption through efficiency measures or self-generation lowers the cost of energy commodities for all consumers in Pennsylvania. This diminishes some of the incentives for managing peak demand, particularly for electric power.
- If aggressive climate policy is successful in mitigating some amount of expected future warming, some opportunities driven by climate change, such as increased warm-weather recreation, will be significantly diminished.
- If significant amount of cropland is converted to forest land in response to certain terrestrial sequestration opportunities, the ability of Pennsylvania's agricultural sector to benefit economically from new warmer-weather agricultural products will be diminished.
- Geologic pore space in Pennsylvania may face conflicting uses, such as CO_2 sequestration and the development of unconventional natural gas sources.

2.0 Introduction

The economy, built environment, human lifestyles, land cover, and ecosystems that exist in Pennsylvania today have co-evolved over the past few centuries, but all are adapted to Commonwealth's prevailing climate. That climate varies across the state, with the topographic features dividing Pennsylvania into four distinct climatic areas: (1) the Southeastern Coastal Plain and Piedmont Plateau, (2) the Ridge and Valley Province, (3) the Allegheny Plateau, and (4) the Lake Erie Plain (PA State Climatologist 2009).

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) concludes that "Warming of the climate system is unequivocal…" and that "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases." The report also finds that "A global assessment of data since 1970 has shown it is likely that anthropogenic warming has had a discernible influence on many physical and biological systems."

As with other regions of the world, Pennsylvania's climate will change over the course of the next century and beyond in response to the substantial increase in atmospheric concentrations of carbon dioxide and other greenhouse gases that followed the development of the world's economy since the mid 1700s. The evolving climate will be defined by changes in the patterns of temperature, precipitation, wind, and other weather variables. The changing regional climate will directly impact climate-sensitive human and natural systems.

This report presents an assessment of the impacts of projected global climate change for Pennsylvania. This assessment was sponsored by DEP which, pursuant to the Pennsylvania Climate Change Act, Act 70 of 2008, is required to develop a report on the potential impacts of global climate change on Pennsylvania's climate, human health, the economy and the management of economic risk, forests, wildlife, fisheries, recreation, agriculture, tourism. Act 70 also requires DEP to report on opportunities, and barriers to their realization, created by the need for alternative sources of energy, climate-related technologies, services and strategies, carbon sequestration technologies, capture and utilization of fugitive greenhouse gas emissions, and other mitigation strategies.

Section 3 of this report presents an overview of the methodology used in the assessment. Section 4 presents a brief overview of the climate system, human-induced climate change, and uncertainty about climate change. A key conclusion of that section is that it is certain that we are on an upward trajectory for global warming through about the year 2035. Regardless of the path that emissions take, by about 2030-2040 we are already committed to a climate change that is slightly more than what we experienced through the 20th century. This is a global response, but a similar response for Pennsylvania is found in the climate projections we develop and present in Section 5. Sections 6 – 13 present assessments for water resources, forests and wildlife, aquatic ecosystems and fisheries, agriculture, energy, human health, tourism and outdoor recreation, and insurance and economic risk. These sections present impacts, adaptation options, and information

needs to improve understanding of impacts and to facilitate beneficial adaptation. Opportunities and barriers created by alternative energy mitigation activities are also examined by sector. The final section 14 synthesizes economic opportunities and barriers.

3.0 Assessment Methodology

Steps in this assessment of climate change impacts include (1) assessing how the Commonwealth's climate might change over the next century, (2) selecting sectors for assessment, and (3) conducting the sector assessments. This overview of the assessment methodology summarizes key elements of these steps.

3.1 Climate Change and Climate Change Scenarios

An essential task in regional climate impact assessment is defining the future regional climate. One approach is to attempt to predict the actual evolution of the regional climate. Climate predictions are not the norm in climate change impact assessments because of the large uncertainties about the future course of greenhouse gas emissions and other factors that drive global climate change, about the response of regional climates to global climate change, and about the course of regional drivers of regional climate (e.g., land cover). Instead, the norm is to use climate change scenarios in which future climates are projected based on assumptions about the path of greenhouse gases and other determinants of climate change.

The projections of Pennsylvania's future climate developed for this assessment are derived from a suite of General Circulation Models (GCMs). GCMs are complex mathematical models that are solved on supercomputers to simulate the earth's climate (see Section 4.2 for more discussion of GCMs). They can be used in a variety of applications, such as short-term (seasonal) climate prediction and, as in this report, long-term (decadal and centennial) projections of the response of the earth's climate to changes in greenhouse gas (GHG) concentrations. The GCM results used here are the same as those used in support of the IPCC AR4; they provide the best scientific information available for projecting 21st century climate at this time. An average of the projections from a suite of GCMs is most often used because model-average backcasts are found to more closely replicate the historical climate record in Pennsylvania in the 20th Century than the backcasts for any individual model, thus indicating greater reliability for the model average than for individual models or subsets.

Climate projections are presented for three 20-year periods in the 21st century (2011-2030, 2046-2065, and 2080-2099), referenced to the recent 20-year period (1980-1999). The use of multi-year averages follows the norms for global climate projections and is done because natural climate variability requires that sufficiently long averages are taken to assess a climate signal. We chose these 20-year intervals to make our results comparable with the IPCC AR4 and many other climate change studies. The three time frames essentially describe climate in the early, middle, and end of the 21st Century. Of the many metrics than can be analyzed in GCM output, we chose those that are both relevant to sectoral assessments and reasonably simulated by GCMs: annual and seasonal means in temperature and precipitation, precipitation extremes, extreme summer heat, growing season length, and frost days.

As indicated above, GCM projections of future climate require assumptions about the future course of global GHG emissions. This assessment uses two plausible emission scenarios to display a range of possible climate impacts depending on what global society does to mitigate greenhouse gas emissions (See Figure 3-1). The scenarios are taken from the IPCC Special Report on Emissions Scenarios (SRES), which describes global GHG emissions in response to alternative world development pathways covering a wide range of demographic, economic and technological driving forces (SRES 2000)(see Appendix 1). The SRES emissions scenarios are widely used in assessments of future climate change and its impacts.

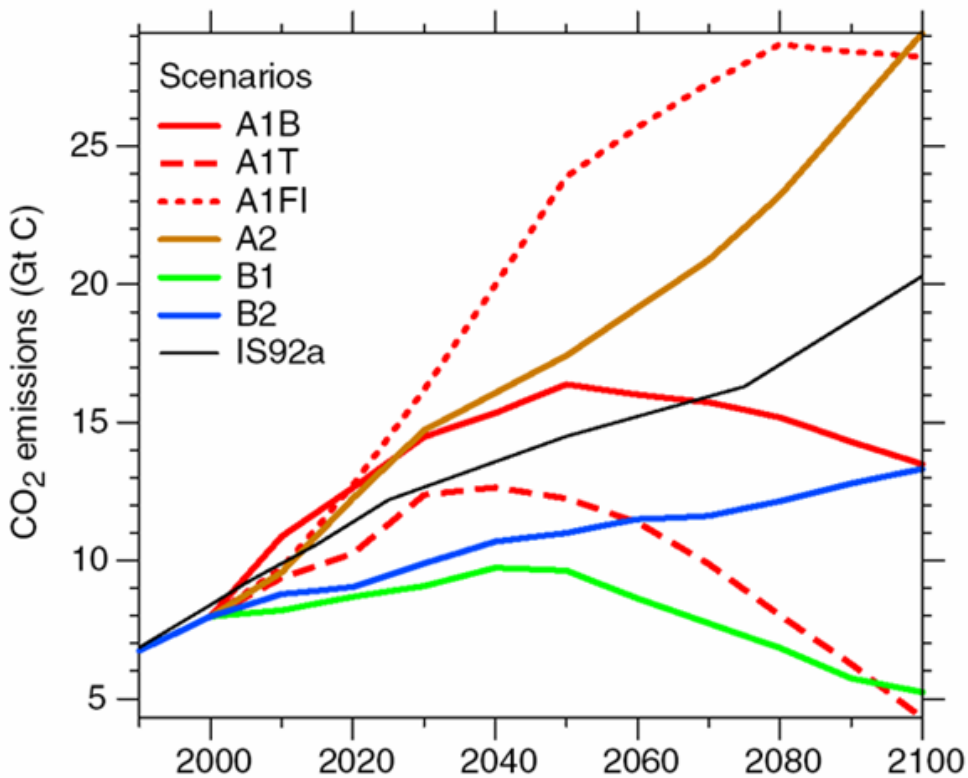

Figure 3.1. Annual CO_2 emissions for the 21st century in gigatons of carbon (Gt C) for a range of possible world development path ways. Source: IPCC 2007a

One of the two scenarios considered in this assessment assumes continued growth in global emissions throughout the 21st Century. This "high" emissions scenario is the IPCC A2 Scenario. The second, lower emissions scenario assumes that emissions growth is moderated to the middle of the 21st century, and declines thereafter to about 50 percent of current rates by the end of the century (global emissions in 2007 from fossil fuel burning, cement manufacturing, and deforestation were about 10 Gt C). This scenario is the IPCC B1 scenario in the Fourth Assessment Report.

The path of future emissions is highly uncertain because the course of world development and global collective actions to mitigate climate change over the next century are highly uncertain. SRES emissions scenarios with more rapid emissions growth than the A2 scenario are available. For example, the Union of Concerned Scientists recent studies of climate change impacts in Pennsylvania and the Northeast used the IPCC A1FI scenario (Frumhoff et al. 2007; Union of Concerned Scientists 2008). Similarly, scenarios with lower emissions than the B1 scenario are available. Our emissions scenario selection is based on the availability of archived GCM output for model averaging, and the frequent use of the A2 and B1 scenarios in recent scientific research on climate change impacts.

Details of our future climate assessment and the results are presented in Section 5 on Pennsylvania's Climate Futures. Importantly, the GCM results we use allow climate projections for the state as a whole but not for particular places or sub-regions of the Commonwealth. This is because the cost of GCM computations precludes the use of fine regional climate grids that would capture climate at small spatial scales. Methods for *downscaling* regional climate change to local climate change exist, but the time and resources available to this study did not permit downscaling of the GCMs to specific places. However, spatial variations across the Commonwealth that exist today are likely to remain in the future because they are due primarily to geographic factors that will remain unchanged in the future such as elevation and distance from the coast. For example, climate in high elevations should remain cooler than the climate in the Piedmont Plain of Southeastern Pennsylvania even though temperatures may rise in each.

3.2 Direct and Indirect Paths of Impact Causation

Global climate change will affect climate-sensitive human and natural systems within a region because it affects regional climate. But global climate change can also affect a region through other economic, demographic, and ecological pathways (Abler et al. 2000a, Najjar et al., 2000) (See Figure 3.2).

For example, global climate change will affect agricultural production across the nation and the planet, affecting global agricultural markets (See section 9). In consequence, Pennsylvania farmers will be affected not only by changes in climatic conditions affecting agricultural productivity, but by changes in prices and agricultural technology induced by global climate change. Similarly, global climate change may affect the spread of invasive species, vector borne diseases, and human populations outside of Pennsylvania in ways that have impacts on Pennsylvania. Indirect impacts are important because they can amplify or counteract direct impacts on a sector, and because they can have greater impacts for a region than the direct impacts (e.g., Abler et al 2000b, 2002). Thus, our assessment is cognizant of direct and indirect pathways of causation.

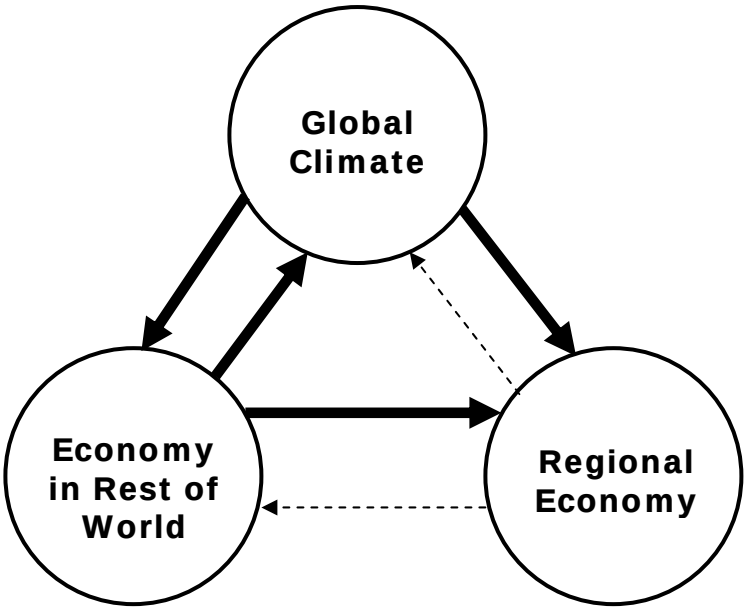

Figure 3.2. Schematic diagram illustrating the interaction of a regional economy with the global economy and the global climate. Solid arrows represent stronger influences than dashed arrows.

3.3 Defining Climate Change Impacts: Baseline Conditions

Concern for the impacts of climate change has led to the development of a language and science of impact assessment. We follow conventions used in the IPCC AR4 (2007b). Climate change impacts can be defined as the difference in human and natural systems with climate change versus without. The baseline (or reference condition) is the state against which change is measured. Some impact assessments use present-day conditions as the baseline. Depending on the system, this may be appropriate, or highly misleading. For example, if a system is highly dynamic and substantially driven by factors other than climate, then present-day conditions will be misleading for defining climate impacts. For example, agriculture has historically been highly dynamic, responding rapidly to changes in technology and markets. We can anticipate the agriculture 25 to 50 years in the future will be markedly different from the agriculture of today without climate change. In consequence, analyzing the impacts of climate change on agriculture using contemporary agriculture at the reference condition would be misleading. Instead, the appropriate baseline is a 'future baseline', which is a projected future set of conditions excluding climate change. Alternatively, for systems that can be expected to evolve little or none at all in the future without climate change, present day conditions may serve well as the reference condition.

Impact assessment is substantially complicated when a "future baseline" is appropriate for impact assessment. This is because the "true" future baseline, that is, what would happen in an assessment domain without climate change, given the long time horizons required in climate impact analysis, is highly uncertain. For example, Pennsylvania, U.S., and global economies have changed radically in recent decades, in ways that were unimaginable 100 years ago. There is no reason to expect that the rapid pace of

economic change will slow down. Products that were unheard of 50 years ago outside of science fiction, such as personal computers, cell phones, industrial robots, satellite communications, and genetic sequencing are commonplace today. New industries have arisen in Pennsylvania and the U.S. around information and medical technologies, even as other industries such as steel have declined. Through all this change there has been significant economic growth: gross domestic product (GDP) per capita in the U.S. (in inflation-adjusted 2000 dollars) rose from less than $14,000 in 1959 to more than $38,000 in 2008 (Council of Economic Advisors 2009).

In economics, forecasting accuracy diminishes rapidly with forecast length, and it would be sheer folly to derive a single set of estimates of economic activity even 10 years into the future, to say nothing of the end of the 21st century. It is likely that the Pennsylvania economy in 2100 will bear only a faint resemblance to the Pennsylvania economy of today, but we do not know what the main changes are likely to be.

Demographic projections are somewhat more reliable than economic projections, largely because most of the people who will be living in Pennsylvania 30 or 40 years from now have already been born. The difficulty with demographic projections for an individual state is that there may be significant movements of people into or out the state from other states and, to a lesser extent, other countries. In-migration and out-migration at the state level are driven in large part by economic conditions: states with growing economies attract people, while states with stagnant economies lose people. Since we cannot make long-term projections of economic conditions at the state (or national) level with any reliability, it follows that we cannot reliably project migration patterns into and out of Pennsylvania over the next several decades.

Here again, due to uncertainty about the future, climate impact assessments typically use scenarios to describe future baseline conditions in significantly dynamic sectors rather than predictions of actual conditions because of the large uncertainties about what the future holds even without climate change. Thus, for example, plausible explicit *socio-economic scenarios* about the course of the economy and society absent climate change, or *ecological scenarios* absent climate change, are required for scientific impact assessment. The various IPCC emissions scenarios are in fact an attempt to do this in general terms for the global economy, but the Pennsylvania economy could take a different path than global trends.

3.4 Defining Climate Change Impacts and Adaptation

Impacts of climate change on natural and human systems can be analyzed as *potential impacts and residual impacts*. Potential impacts refer to impacts that may occur given a *projected change in climate*, without considering adaptation that may occur in natural and human systems to climate change. Residual impacts refer to the impacts of climate change that would occur after adaptation. Adaptation is defined as the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Adaptations may occur through various processes, including proactive, planned actions to avoid harm or

exploit opportunities from expected climate change, or as systemic responses to realized climate change. Contemporary land use restrictions to minimize the expansion of impervious surface area to reduce flood risks from more intense rainfall events is an example of a proactive, planned action in response to expected climate change. A farmer's change in crop selection due to changes in realized weather patterns would be an example of a market-driven, human systems response. Another example of a systems response to realized climate change would be migration of coastal wetland inland, when possible, with sea-level rise.

The distinction between potential and residual impacts highlights the importance of considering possible planned and systemic responses to climate change in impact assessment. The AR4 finds that "…there is growing evidence since the IPCC Third Assessment of human activity to adapt to observed and anticipated climate change. For example, climate change is considered in the design of infrastructure projects such as coastal defense in the Maldives and The Netherlands, and the Confederation Bridge in Canada. Other examples include prevention of glacial lake outburst flooding in Nepal, and policies and strategies such as water management in Australia and government responses to heat waves in, for example, some European countries (IPCC 2007b, p.17)."

Beyond understanding the impacts of climate change, analysis of adaptation options is essential for coping with climate change. This is because the most aggressive strategies to reduce greenhouse gas emissions cannot reverse the course of climate change in the next few decades. Past emissions have put the earth on a course of unavoidable climatic change (IPCC 2007b). Adaptation is therefore the first line of action that can be taken to address harms or benefits that may emerge in the next few decades.

3.5 Sector Selection for Impact Assessment

Most of the sectors considered in this report were mandated by Act 70 of 2008. Other sectors were added in consultation with DEP. Criteria for selecting additional sectors, and that guided the depth with which all are examined included: (1) the importance of the sector to the state's economic and social wellbeing, and ecological health; (2) the expected sensitivity of the sector to climate variability and change; and (3) the data and scientific results available to perform a credible assessment given the limited time and resources available. Table 3.1 presents a summary of the sectors examined and the structure of the report.

Section Title	Section #	Assessment Domain(s)
Agriculture	9	Climate impacts on agricultural production and income Environmental impacts of climate change mediated through agriculture Opportunities, and barriers to achieving them, related to alternative energy and climate mitigation in agriculture Adaptation opportunities and challenges in agriculture Information needs
Aquatic Ecosystems and Fisheries	8	Climate change impacts on aquatic ecosystems including fisheries Adaptation opportunities and challenges in aquatic ecosystem management Information needs
Economic Barriers and Opportunities	14	Synthesis of opportunities created by the need for alternative energy, and other mitigation technologies and activities, and barriers to achieving them.
Climate Change and Uncertainty	4	Background on the climate system, climate change, and uncertainty in climate projections
Energy	10	Climate impacts on energy demand and production Changes in ecosystem services (environmental impacts) of climate change mediated through the energy sector Opportunities, and barriers to achieving them, related to alternative energy and climate mitigation in energy Adaptation opportunities and challenges in energy Information needs
Forests and Wildlife	7	Climate impacts on forest composition, production, and income Changes in ecosystem services (environmental impacts) of climate change mediated through forests, including wildlife and fisheries Opportunities and barriers to achieving them related to alternative energy and climate mitigation in forestry Adaptation opportunities and challenges in forests Information needs

Human Health	11	Climate impacts on human health Adaptation opportunities and challenges in human health Information needs
Insurance and Economic Risk	13	Climate change impacts on the management of economic risk and the insurance industry Opportunities and barriers to achieving them related to alternative energy and climate mitigation in insurance Adaptation opportunities and challenges in insurance Information needs
Pennsylvania's Climate Futures	5	PA Climate Futures
Tourism and Outdoor Recreation	12	Climate impacts on outdoor recreation, including hunting and fishing, and climate sensitive tourism Opportunities and barriers to achieving them related to alternative energy and climate mitigation in outdoor recreation Adaptation opportunities and challenges in tourism and outdoor recreation Information needs
Water Resources	6	Impacts of climate change on water resources and hydrology, including impacts on water- and hydrology-based ecosystem services (e.g. fisheries) Adaptation opportunities and challenges in water management Information needs

Table 3.1 Section Guide

3.6 Sectoral Impact Assessments

Ideally, the impact of projected climate change on any given sector is assessed using a mixture of approaches, including integrated quantitative modeling of the sector and extensive stakeholder engagement. The limited time and resources available to this assessment necessitate that the findings are based on readily available data, literature, and some preliminary quantitative analyses. It is important to note in this context that there is only a limited scientific literature addressing the impacts of projected climate change in Pennsylvania explicitly. In consequence, this assessment must in large degree interpret the implications for Pennsylvania of scientific literature and data that do not apply explicitly to Pennsylvania.

In conducting the sectoral assessments, we are cognizant that there are multiple stressors that affect each sector that influence the impacts of climate change. For example, climate change will affect the demand for energy for heating and cooling, but the impacts of these demand changes on the energy sector will also depend on how climate mitigation policies influence the structure of energy production. We are also cognizant of interactions between sectors. For example, water quality and aquatic ecosystems will be directly affected by climate-induced changes in temperature and precipitation, but it will also be affected by climate-induced changes in agricultural practices that affect nonpoint pollution, a leading cause of water quality impairments.

3.7 Uncertainty

Uncertainty in climate impact assessment is large and stems from multiple causes. There is uncertainty about future climates due to imperfect knowledge of the paths of the drivers of climate change and the response of global and regional climates to climate stressors. There is uncertainty about baseline conditions, and about the impacts of climate change on human and natural systems. This assessment acknowledges this uncertainty and addresses it explicitly in each section. In some cases, most notably in the section on water resources, uncertainty is addressed through a mixture of quantitative and qualitative methods. More generally, however, time and resources available for the assessment limit the assessment of uncertainty to qualitative characterizations. The authors of this report are informed by the IPCC guidance for lead authors for addressing uncertainties (IPCC 2005) in their presentation of results.

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4.0 Climate Change and Uncertainty

This section provides a basic background of the climate system, including some of the fundamental physical processes that maintain the earth's mean temperature, feedbacks that may influence how the climate responds to perturbations (such as increases in greenhouse gases), as well as some examples of natural climate variations. Uncertainty in climate projections is also discussed, including uncertainty in emissions scenarios and the representation of physical processes in General Circulation Models (GCMs).

4.1 The Climate System and Greenhouse Effect

The energy that drives the climate system comes almost entirely from the sun. There is a small amount of geothermal energy released at the surface, but this has no direct impact on global climate. Indirectly, however, this internal heat source is important over both long and short time scales through the actions of plate tectonics. Tectonic processes result in volcanic eruptions that release CO_2 and sulfate aerosols, both of which affect climate in different ways. Over long time periods, tectonic processes also determine the distribution of oceans and continents and the location and height of mountain ranges—all of which have a significant impact on global and regional climates. For our purposes we can ignore these tectonic processes, except for the short term effects of volcanic eruptions. The greenhouse gases released from volcanoes accumulate slowly in the atmosphere over long periods of time. On human time scales the main effect of volcanoes is the production of sulfate aerosols in the stratosphere that increase the albedo (see below) and slightly cool climate for 1-3 years following major eruptions.

Solar radiation enters the atmosphere where it is absorbed by atmospheric gases or is transmitted downward to warm the surface. Some portion of this incoming radiation is scattered back out to space, primarily from the surface, from aerosols in the atmosphere, and from clouds. This reflected fraction is referred to as the planetary albedo (α), which, under current climate conditions, is about 30 percent of the incoming energy and is largely determined by snow and ice cover and by the distribution of clouds. The solar radiation absorbed by the atmosphere, land, and ocean warms the system, and earth then emits radiation to space. This electromagnetic radiation is emitted as a function of absolute temperature (T) according to the Stefan-Boltzmann Law:

$$W - \sigma T^4 , \qquad 4.1$$

where W is the amount of radiation emitted and σ is the Stefan-Boltzmann constant. This equation holds for what is known as a blackbody: an object that absorbs and emits all of the radiation theoretically possible at a given temperature. The sun acts as a blackbody, while earth is not quite as efficient.

Under equilibrium conditions, the radiation received from the sun must be balanced by radiation emitted from earth. If this wasn't the case, then earth would get continuously hotter over time as it received more energy than it lost or, if it lost more than it received, the planet would get continuously colder. It is very simple to calculate how much radiation the planet receives from the sun. Knowing this incoming radiation must balance

with the radiation emitted to space, a simple climate model that calculates the mean global temperature (T) of the planet can be derived:

$$T = \frac{\sqrt[4]{S_o(1-a)}}{4\sigma} + GH \qquad 4.2$$

where S_o is the solar constant (the amount of solar energy per square meter reaching the top of earth's atmosphere) and GH is a greenhouse parameter that slightly raises the calculated temperature.

The outer edge of the sun (where the radiation we receive is emitted) has a temperature of about 6000 K (11,000 degrees F). The earth has a temperature of about 288 K (59 degrees F). The sun emits much more radiation per square meter than does earth, but this amount is considerably reduced by the time the radiation reaches the planet (actually, the radiation isn't reduced; it is simply spread out over a much larger area). The other difference between the solar and terrestrial (earth) radiation is the wavelength. Hotter objects emit at shorter wavelengths and cooler objects emit at longer wavelengths. This is important in the discussion of global warming because the way atmospheric gases and water droplets (clouds) interact with radiation changes as a function of wavelength. Earth's atmosphere is relatively transparent for the shorter wavelengths emitted by the sun, and about half of the incoming solar radiation is transmitted through the atmosphere and absorbed at the surface. The surface then emits longwave radiation, but there are a number of atmospheric gases that absorb at these wavelengths (primarily CO_2, and methane, but most importantly—water vapor). Some of the longwave radiation emitted from the surface is, therefore, absorbed by the atmosphere. The atmosphere then

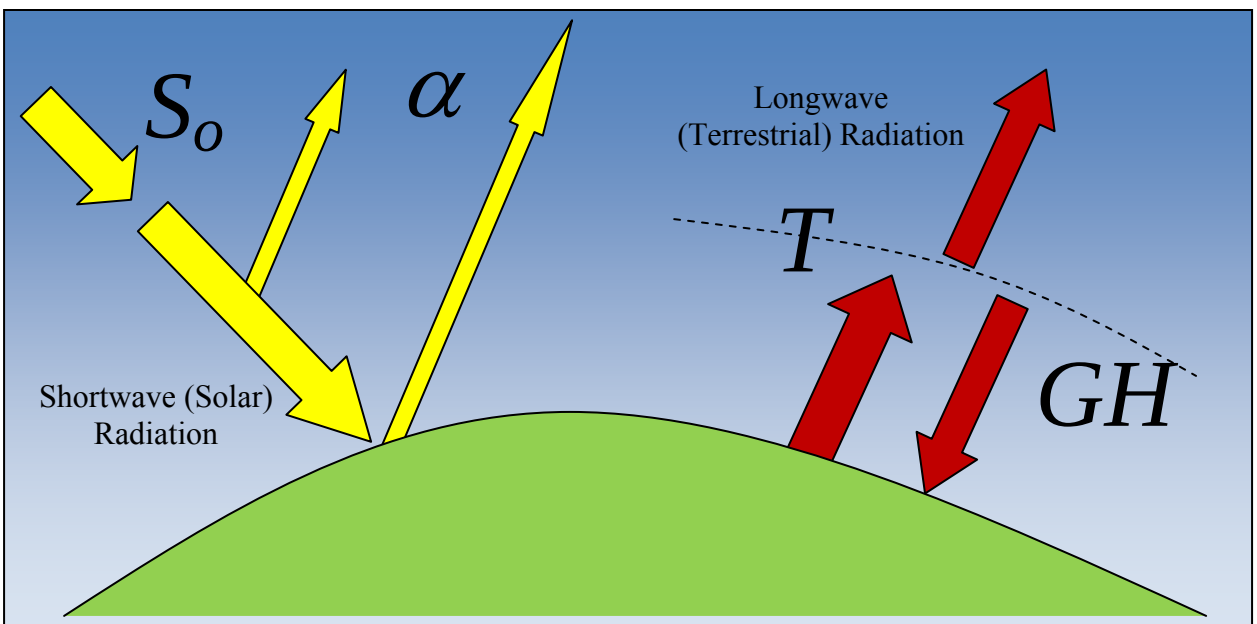

Figure 4.1: The Greenhouse Effect. Labels refer to the terms in Equation 4.1

reradiates the energy—some of which is radiated upward to higher levels and eventually out to space, and some of which is radiated back toward the surface (Figure 4.1). It is this downward, component that constitutes the greenhouse effect. Essentially, this radiation is trapped within the system and raises earth's temperature slightly above what it would otherwise be. In Equation 4.2, without the additional greenhouse contribution, and for the present solar constant and planetary albedo, the mean global temperature would be 255 K (0 degrees F): 18 K (32 degrees F) below the freezing point of water. With the additional greenhouse contribution earth's temperature is a much more tolerable 288 K (59 degrees F).

Equation 4.2, which shows that the mean global surface temperature is controlled simply by the amount of the incoming solar radiation, earth's albedo, and the greenhouse parameter is very useful for understanding climate change. On short time scales, the incoming solar radiation changes very little. At the peak of the last glaciation, roughly 18,000 years ago, there was an ice sheet several kilometers thick over a large part of North America. The edge of the ice sheet was close to the Pennsylvania/New York border. Pennsylvania would have looked like the unglaciated parts of Greenland today – cold, windswept and barren. The difference between the mean global temperature then and now is on the order of only 6 degrees C (10 degrees F), although the local increase in temperature was obviously a lot greater. A mean global temperature increase of 1.5 degrees C-3.5 degrees C (3-6 degrees F) by the end of this century, approximately the likely range for the B2 scenario in the IPCC Fourth Annual Assessment, is 25 percent to 50 percent of the change needed to reach today's climate from a world where ice sheets like Greenland and Antarctica covered large areas of North America and Eurasia. A full cycle, which includes cold (glacial) and warm (interglacial) climates, happens over about 100,000 – 120,000 years and we have had multiple cycles over the last 2 million years. The general pattern is one in which there is long term gradual cooling, followed by a fairly rapid warming and then a 10,000 – 12,000 year warm interval, before the cooling begins again.

Apart from placing projected future warming in context, consideration of past climate change is relevant to our discussion of global warming in several ways. To begin with, these glacial cycles are driven by relatively small changes in earth's orbital characteristics. These have little impact on the total amount of radiation earth receives, but they do alter the seasonal distribution. In other words, the direct solar forcing is very small, the earth's climate response is much greater. Ice ages happen when the orbital characteristics result in cooler Northern Hemisphere summers. This allows more snow and ice to persist through the summer, which, over time, allows the ice sheets to build.

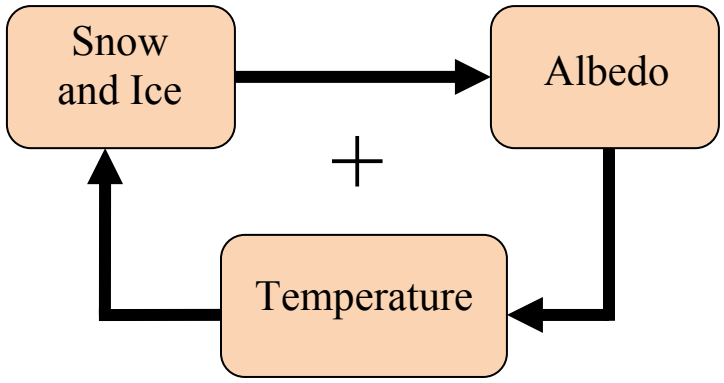

Figure 4.2. Diagram illustrating Snow/Ice – Albedo feedback.

The direct solar forcing, however, is nowhere near enough to create such a large change in the climate system. The reason we have the ice ages is because of positive feedback processes that amplify the initial change. The most important is the ice-albedo feedback, which also plays a significant role in future global warming. Once snow and ice begins to accumulate, because of its high reflectivity it increases the albedo. A higher planetary albedo reduces the amount of solar radiation that is absorbed at the surface, this reduces temperature, which in turn allows more snow and ice to form (Figure 4.2). The increased ice further increases albedo, reduces temperatures and grows more ice, etc.—in a positive feedback loop. The same feedback plays a major role in simulations of future greenhouse warming. In this case the feedback is moving in the opposite direction. A small increase in temperatures results in a small reduction in snow cover over land and ice cover over the oceans, this reduces the albedo (so more radiation is absorbed), which then raises temperature, melts more ice, and so on. This feedback, along with others that involve ocean-atmosphere heat exchanges, dominate the model response at high latitudes, which explains why the warming over the Arctic is significantly greater than the global mean.

Just like with the glacial cycles, when we look to the future, the actual change in the greenhouse effect (i.e. the direct forcing on the climate system) is relatively small. The relatively large response that is projected occurs because of positive feedback processes like the ice-albedo feedback. One of the most important of these involves changing cloud cover. Increased warming from greenhouse gases increases evaporation and cloud formation, which then feeds back to further change temperature. The feedback process in this case is much more complicated than with the snow and ice cover because clouds both reflect solar radiation (so they cool the system) and at the same time absorb longwave radiation (so they enhance the greenhouse effect and warm the system). Which feedback dominates depends on (amongst other things) the altitude of the cloud and its geographic location: low-level clouds over the tropical ocean have a greater albedo effect than greenhouse effect and tend to cool the system; high level cirrus does the opposite. This type of complexity is the reason we can only address questions of future warming through the use of high resolution numerical models.

Before leaving the topic of feedback processes, it is worth making two further observations. The first is that most of the climate system feedbacks that have been identified tend to be positive—that is they amplify the initial change. As we will show in Section 4.3 and in Chapter 5, the current generation of climate models does a reasonable job of simulating the 20th century climate at global and regional scales, and also matches reasonably well the climate reconstructions for the past 1,000 years (Hegerl et al., 2007). This suggests that GCMs have included most of the relevant feedback processes. There is the chance, however, that as we move toward a warmer world, there may be other positive or negative feedback processes that are either not included or not well simulated in the present models. Negative feedbacks are ones that dampen the initial change.

Secondly, as we moved out of the last glacial period, climate was warming and the ice had retreated well northward when there was sudden and rapid reversal to ice age conditions, particularly in the region surrounding the North Atlantic. This cold period, referred to as the *Younger Dryas*, lasted for approximately 1,300 years, from about 12,900 to 11,600 years before present. What is significant about this is that the

transitions into and out of the event were extremely rapid, taking place on a timescale of years to decades. This Younger Dryas event is the classic example of what is now referred to as *abrupt climate change* where the climate system seems to shift rapidly between two different quasi-stable states following a relatively small perturbation. There is no guarantee that as we push the climate toward a warmer state, a similar abrupt change will not occur. The bottom line is that, although we are reasonably confident about GCM projections of future climate, there are still unknowns in the climate system and still room for some surprises. A case in point may be the Greenland Ice Cap, which appears to be melting at a much faster rate than models would have suggested.

4.2 General Circulation Models

General Circulation Models describe the climate system with a set of physical equations that calculate the transfers of energy, mass and momentum within and between the major components of the Earth System (atmosphere, ocean, land/vegetation, cryosphere). The models are initialized (that is they are given the state of the atmosphere, ocean etc. at a particular point in time) and then they are integrated forward, computing a new state at each time step. However, the climate system is chaotic. Essentially, this means it is highly dependent on the initial state and, as the computations are run forward in time, very small differences in the starting point can lead to very different solutions after only a short period of time. The impacts of this manifest themselves in a variety of ways. This explains, for example, why weather forecasts are only relatively useful over a few days. After a week, the accuracy of the forecast is considerably reduced, and after about two weeks there is virtually no predictive capacity. This is not a function of data quality, computing power, or our understanding of meteorology—it is simply an inherent characteristic of the system. For this reason, we can't run a model of the climate system forward in time and predict (forecast) what the weather will be at a specific point in the future. What we can do is simulate the large scale features of the climate, and its behavior over future time periods, by running numerical models that contain the physics of how the climate system works; constrained, for example, by the present distribution of land and oceans and the incoming solar energy; and forced by the changing gas composition of the atmosphere. What we would expect from such models is the ability to simulate realistic patterns of spatial and temporal variability in the major features of climate system over some specified time period.

4.3 Causes of Recent Climate Change

General Circulation Models are an important tool for assessing the causes of recent climate change. Climate models run with only natural forcings (solar variability and volcanoes) do not reproduce the observed climate change over the 20th century, as shown in Figure 4.3, including the warming of Pennsylvania and the Northeast U.S. However, when the observed trend in greenhouse gases is added to the climate models, the observed warming is largely captured. Statistical approaches, which do not rely on complex climate models, generally produce the same result—that warming of the climate system over the 20th century cannot be explained based on natural forcing and natural variability alone (Lockwood and Frohlich, 2007, 2008; Lean and Rind, 2008; Lockwood, 2008). Though there are some suggestions that the sensitivity of climate to greenhouse

gases has been overestimated by GCMs (e.g., Schwartz, 2007; Scafetta and West, 2007), these studies are in the minority, and are balanced by studies suggesting that the climate sensitivity of GCMs has been underestimated (e.g., Sokolov et al., 2009).

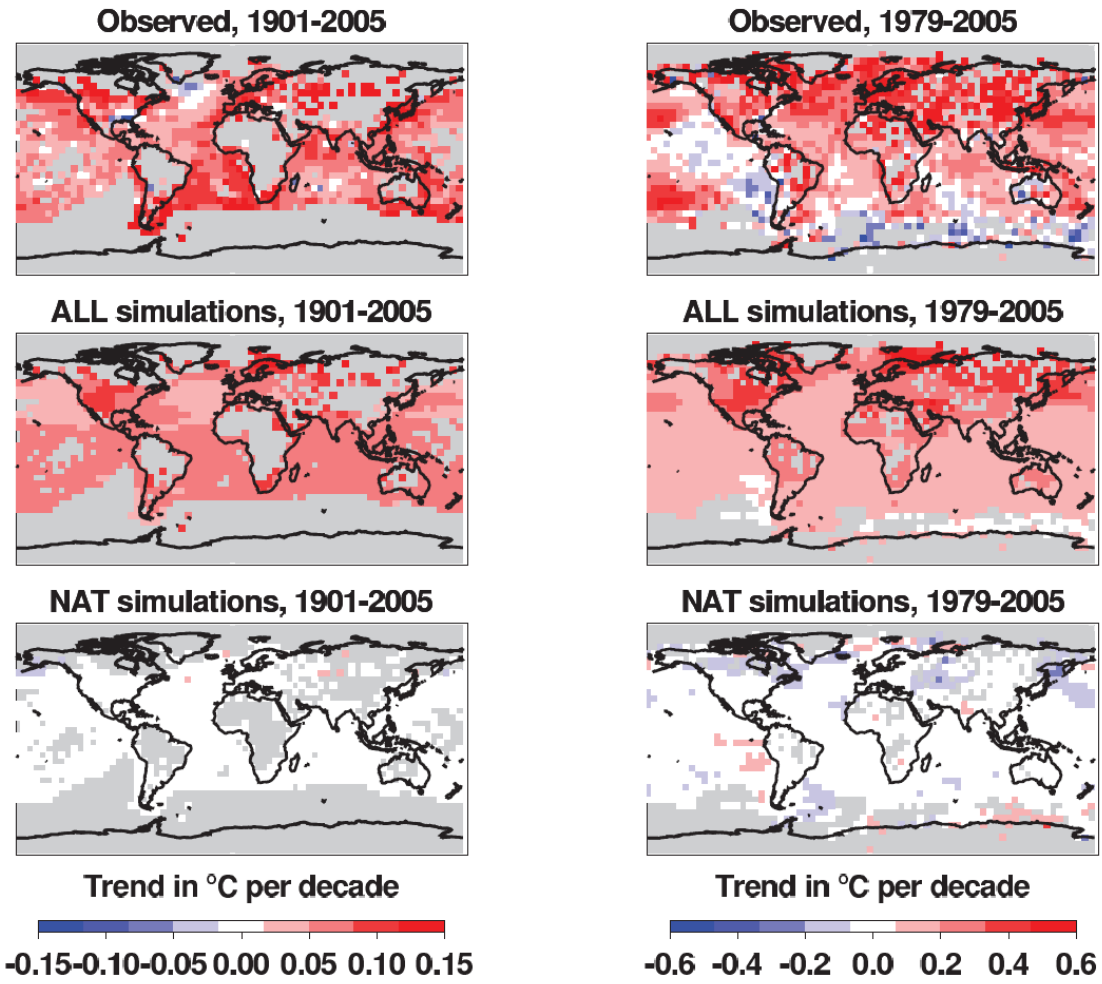

Figure 4.3. Trends in observed and simulated temperature changes over the 1901 to 2005 (left column) and 1979 to 2005 (right column) periods. First row: trends in observed temperature changes. Second row: multi-model average trends from models including both anthropogenic and natural forcings. Third row: multi-model average trends from models including natural forcings only. Grey shading indicates regions where there are insufficient observed data to calculate a trend for that grid box. *(Figure 9.6 from Hegerl et al., 2007)*

There has been increased interest, especially on the Internet and in media outlets, in the global temperature trend since 1998, which has shown little long-term change (though the average since 1998 is well above the long-term trend). The lack of a trend since 1998 is due to the unusually large El Niño event of 1997 (e.g., Fawcett, 2008), that produced a spike in the temperature record and a subsequent recovery. Such periods of small or even negative 10-year temperature trends are not uncommon during the past 100 years, despite an overall, statistically significant long-term warming (Easterling and Wehner, 2009). In addition to being able to simulate the long-term trend, climate models capture the probability distribution of short-term trends, and we can expect, even into the future, some short-term trends that are small or even negative (Easterling and Wehner, 2009). This reveals the importance of having long-term climate records for understanding the causes of climate change and variability.

4.4 Uncertainty in Climate Projections

Such models have the same dependence on initial conditions as do the weather forecast models. This means that if we run a model forward in time and extract from that the climate patterns for a 20-year period—say 2046-2065, a common time period used in the IPCC analyses—we will get one view of a possible future. If we change the starting point for the model just very slightly, we will end up with a second view that would be broadly similar, but could also have some significant differences. Over the 20 years we might expect to see similar average conditions over North America and similar degrees of variability from year to year. In one run of the model, for example, '2050' may be anomalously warm and wet over Pennsylvania, and in the other run it may be anomalously cool and dry. The message to take from this is that if we look over a sufficiently long period, say a 20-30 year window, and over a relatively large spatial scale, say averaging over the mid-Atlantic region, then we would expect a reasonable projection of what the climate system will be like in terms of mean fields and their spatial and temporal variability. As we attempt to focus in on smaller areas and shorter time periods, the results become much more uncertain.

Looking at Figure 4.4 from the IPCC AR4 we see a different form of uncertainty. This figure shows temperature projections over North America from a suite of different models, all driven by the same atmospheric forcing (i.e. a particular greenhouse gas emission scenario). Looking at the Eastern U.S., the orange shading encloses the envelope of projections from the 21 models used in the IPCC AR4 for a single emission scenario; the colored bars to the right indicate the range of results for 2100 for several different scenarios. What is of interest for the present is the projection out to 2100 for the single emission scenario. The first, and most obvious, observation is that despite the fact that these models all contain similar physics and are being driven by the same forcing, they give different results, and at any point in time we have a spread of possible temperatures. Note that the projected change and the spread is approximately the same across the U.S., but both the magnitude of change and the difference between the models increase at higher latitudes. Figure 4.5 shows the IPCC simulated distribution of precipitation over North America. The figure shows the model simulated annual, summer and winter temperature and precipitation differences for the A1B scenario (2080-2099 minus 1980-1999) averaged over 21 models. The third row shows the number of

models out of 21 that produce an increase in precipitation in the future. Note particularly the summer months where 8-13 of the models show an increase in precipitation over Pennsylvania, indicating that one third or more of the models are showing no change or a decrease in rainfall. While there is good agreement for the direction of change in the winter, there is very little agreement in summer.

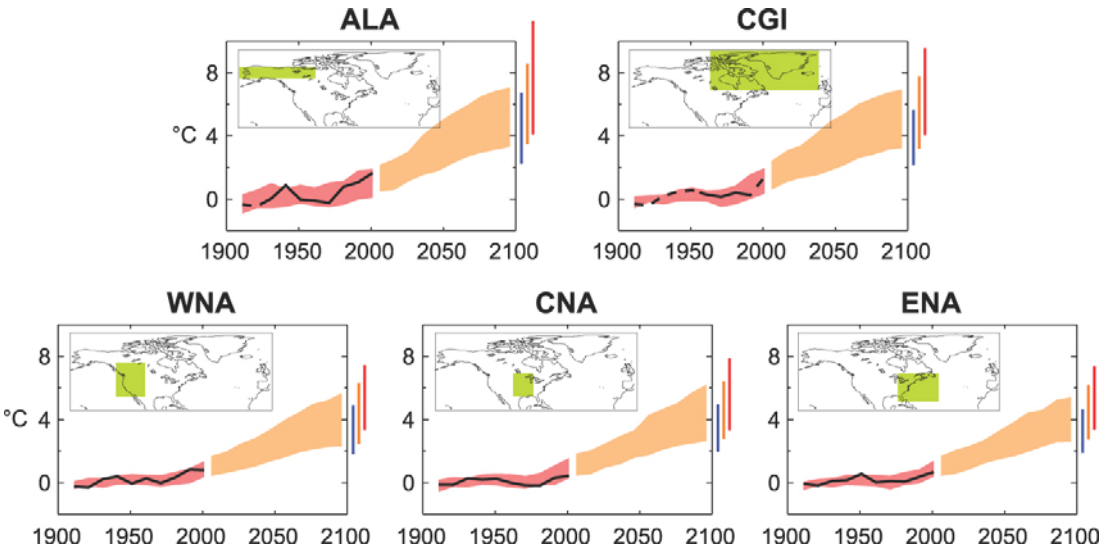

Figure 4.4 Temperature Projections for North America. *(Figure 11.11 from Christensen et al., 2007.)*

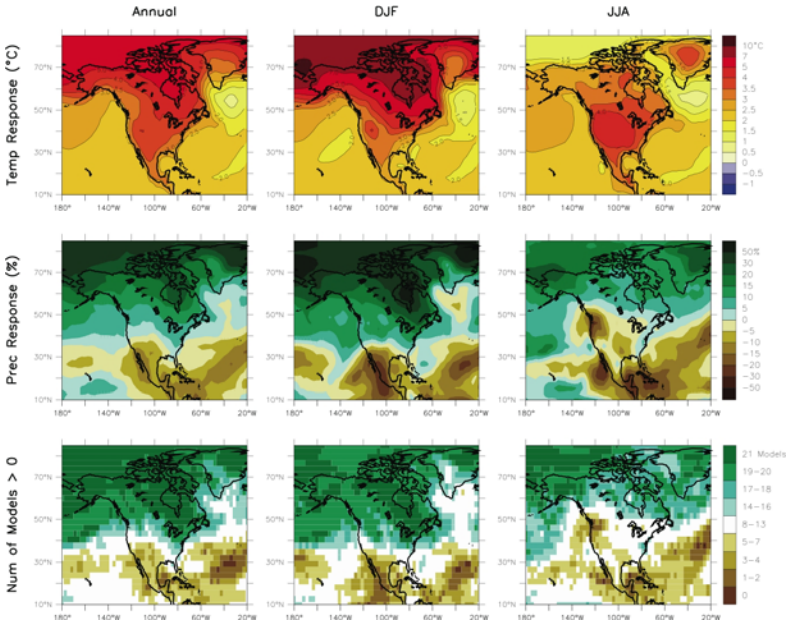

Figure 4.5. Temperature and precipitation differences (2080-2099 – 1980-1999). (*Figure 11.12 from Christensen et al., 2007.)*

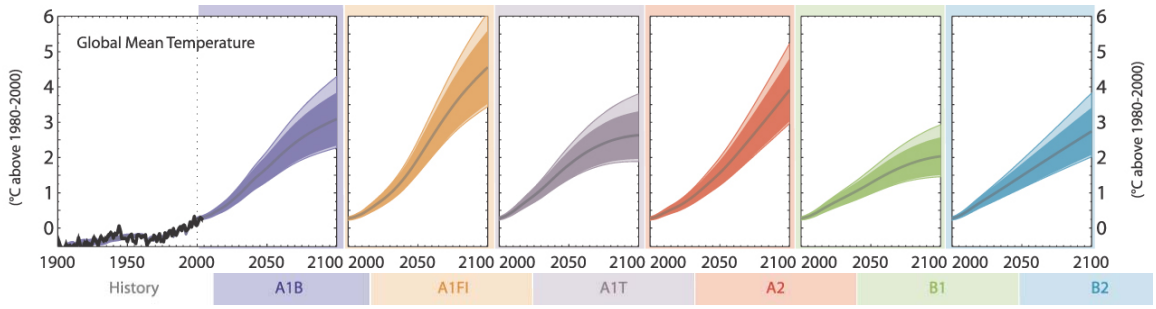

Figure 4.6 Global temperature projections under a range of different CO_2 emissions scenarios. *(Figure 10.26 from Christensen et al., 2007.)*

These differences between the models arise from several sources. Although the models all have similar physics, they are not identical. In particular, they differ in the ways they treat some of the more important feedback processes. Differences in the way they treat clouds, for example, accounts for a significant proportion of the models' sensitivity to change. The result of all of these differences is that some models may develop a bias (e.g. generally warmer and wetter or colder and drier than the observed climate); some may simulate high latitude processes better than others, some may do better over the tropical oceans, etc. On a global basis, no model does better than all of the others and even models that appear to perform less well over much of the globe, still perform better than many others in some regions (see, for example, Cai et al., 2009). Research is continuing to determine the most effective ways to evaluate models and to combine the output from multiple models. For temperature and precipitation, there is no obvious reason for excluding any particular model and many of the results presented in Section 5 are obtained simply by averaging or taking the median of all available output.

A third source of uncertainty lies in the choice of future emissions scenarios. Figure 4.6 shows global mean temperature projections for a range of possible emissions scenarios. The temperature projections are based on a very simplified climate model tuned to the temperature response of 19 of the IPCC GCMs. The dark shaded areas represent the mean ±1 standard deviation. The lighter shaded areas illustrate the change that results from assuming lower or higher carbon cycle feedbacks. The details are less important here than the observation that the future climate response is highly dependent on the assumptions we make about the factors that determine future greenhouse gas emissions.

4.5 Making Sense of the Uncertainty

Figure 4.7 shows mean global temperature projections for three emissions scenarios, including the two used in this report (the A2 and B1 Scenarios). The black line shows the

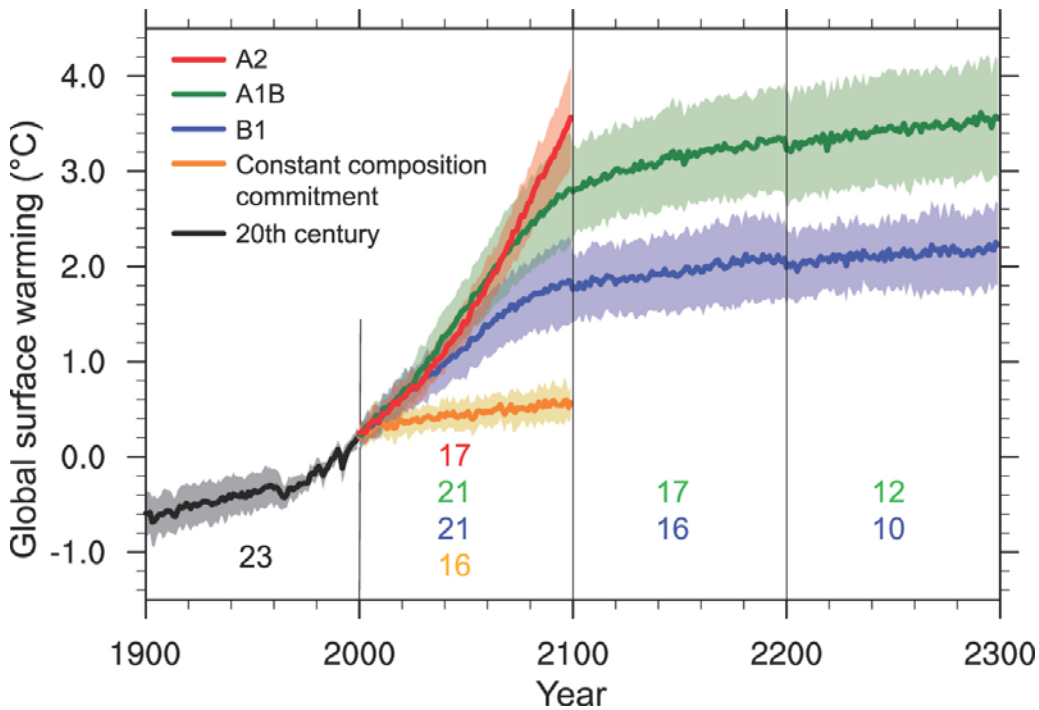

Figure 4.7 Mean global temperature projections out to 2300. *(Figure 10.4 from Christensen et al., 2007.)*

20th century simulation with the variability about the mean. The colored lines show the projection through the 21st century: the solid line is the mean and the shading denotes the ± 1 standard deviation in the individual model means. The orange line indicates the climate change we would be committed to if we had held atmospheric CO_2 constant at the year 2000 level. For the A1B and B1 scenarios, the continuing projections out to 2300 is the additional warming that would be expected by holding atmospheric CO_2 constant at the year 2100 level for each scenario. We can make several important observations from these curves:

1. We did not hold CO_2 levels constant at the year 2000 level, so the orange trajectory is no longer possible.
2. The earth is on an upward trajectory and, through about the year 2035, it makes no difference what actual emission trajectory we follow. By about 2030-2040 we are already committed to a climate change that is slightly more than what we experienced through the 20th century. This is a global response, but we will see a similar response for Pennsylvania in the results presented in Section 5.
3. Despite the uncertainty in model projections, the models have been shown to produce reasonable simulations of the 20th century climate, which gives some confidence about their simulations of future climate. While there is some uncertainty due to current model limitations, by 2100 the difference between scenarios is greater than the variability in model simulations of any given scenario. That is, the uncertainty is dominated by the difficulty of projecting socio-economic change rather than our ability to model the climate system.
4. Based on current state of our understanding and our modeling capability, we can be reasonably confident about a 0.6-0.8^{o}C mean global temperature change through the first third of the century and a change that is not likely to be much less than about 1.5^{o}C by 2100. With no mitigating action, the change is likely to be twice that, if not more.

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5.0 Pennsylvania's Climate Futures

This section presents past and future climate simulations for Pennsylvania from a suite of General Circulation Models. We present past simulations to provide an assessment of the reliability of the GCMs for the Commonwealth. Our focus is on daily mean surface temperature and precipitation, and metrics computed from these (such as number of consecutive dry days), because these are the master variables that determine many of the important impacts on the sectors considered in this assessment. There are also excellent observational data sets for these variables, which facilitates model evaluation. For some metrics, such as storm intensity and frequency, we did not have the resources to conduct our own analyses; in these cases we relied on previously published studies.

5.1 The Climate Models

GCM output was acquired from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al. 2007). Daily and monthly averages of 2-m temperature and precipitation data were downloaded for 14 models (Table 5.1). These were selected from the 23 CMIP3 models based on the availability of daily output of temperature and precipitation for the two greenhouse gas scenarios of interest. Unfortunately, daily output was not available for some of the models in Table 5.1 for the early part of the 21st century, and so projections of metrics based on daily output are not presented for this time period.

Table 5.1. General Circulation Models used for this study.

Originating Group(s)	Country	CMIP3 I.D.
Bjerknes Centre for Climate Research	Norway	BCCR-BCM2.0
National Center for Atmospheric Research	USA	CCSM3
Canadian Centre for Climate Modelling & Analysis	Canada	CGCM3.1(T47)
Météo-France / Centre National de Recherches Météorologiques	France	CNRM-CM3
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.0
CSIRO Atmospheric Research	Australia	CSIRO-Mk3.5
Max Planck Institute for Meteorology	Germany	ECHAM5/MPI-OM
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group.	Germany / Korea	ECHO-G
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.0
US Dept. of Commerce / NOAA / Geophysical Fluid Dynamics Laboratory	USA	GFDL-CM2.1
Institute for Numerical Mathematics	Russia	INM-CM3.0
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan	MIROC3.2(medres)
Meteorological Research Institute	Japan	MRI-CGCM2.3.2
National Center for Atmospheric Research	USA	PCM

For historical analysis, output was acquired for "the climate of the twentieth century" (20C3M) experiment; for 21st century projections we have considered the IPCC Special Report on Emission Scenarios (SRES) B1 and A2 experiments (see emissions trajectories in Figure 3.1). The time periods used in this assessment mirror those used for the IPCC AR4: 1980-1999, 2011-2030 (early 21st century), 2046-2065 (mid 21st century), and 2080-2099 (late 21st century). Many models were run for multiple realizations (i.e., with initial conditions slightly altered but still within observational error). Average horizontal resolution of the models varies between about 1.5 degrees and 4.5 degrees. The models also vary substantially in complexity and parameterization of subgrid scale processes.

5.2 Observations

Two data sets were used in the model evaluation, one for characterizing long-term statistics in monthly means and the other for characterizing sub-monthly variability. The former is from the University of Delaware (Matsuura & Willmot 2007a, b), which is a temperature and precipitation time series of monthly averages from 1900 to 2006 on a 0.5 degrees grid, based on multiple station data sets, including the Global Historical Climatology Network. Temperature and precipitation data were interpolated to this grid using a variety of methods, including climatologically aided interpolation (Willmot & Robeson 1995). Surface elevation was also used in the gridding of temperature (Willmott & Matsuura 1995).

The data set for submonthly variability in temperature and precipitation is from the North American Regional Reanalysis (NARR), which uses data assimilation to determine the state of the atmosphere over North America at high spatial (32 km) and temporal (3 hr) resolution from 1979 to the present (Mesinger et al. 2006). We have used daily averages from the NARR.

5.3 Processing of Data Sets

GCM output and observational data were placed on a 1 degrees grid for Pennsylvania; Pennsylvania spans roughly 2 degrees in latitude and 6 degrees in longitude, so a total of 12 grid boxes were used (Figure 5.1). GCM output was linearly interpolated to this grid whereas observational data were averaged within each 1 degrees grid box. Six main metrics were computed to provide a first-order quantitative assessment of the models (Table 5.2). The annual cycles in mean temperature and precipitation describe the average year. The interannual variability metric characterizes the variability of a given calendar month from year to year (e.g., severe winters vs. mild winters). Finally, the intramonthly variability is a measure of how variable conditions are within a calendar month (e.g., a cold snap vs. a warm spell).

Table 5.3 lists the additional metrics that were computed for particular sectoral applications. The first four metrics in the table highlight precipitation extremes: extremely wet and dry periods (metrics 1 and 2), and the intensity of precipitation (metrics 3 and 4). The agricultural metrics used are growing season length and the number of frost days, which are both temperature-based metrics (Frich et al, 2002). The

growing season starts at the first period in the year when the daily mean temperature is above 5 degrees C (41 degrees F) for at least five days and it ends when the daily mean temperature is less than 5 degrees C (41 degrees F) for at least 5 days. Frost days are defined as the number of days when the daily minimum temperature is below the 0 degrees C (32 degrees F). Finally, the extreme heat metric chosen quantifies heat waves: the number of consecutive days in which the high temperature is above a given threshold.

The metrics in Tables 5.2 and 5.3 were computed for each of the 14 GCMs as well as for the multi-model average. Multiple realizations for a given model were first averaged before computing the multi-model average. All of the metrics in Tables 5.2 and 5.3 are based on averages over the state. For example, the number of days in which the daily maximum temperature is above 85 degrees F refers to the daily maximum temperature averaged over the state.

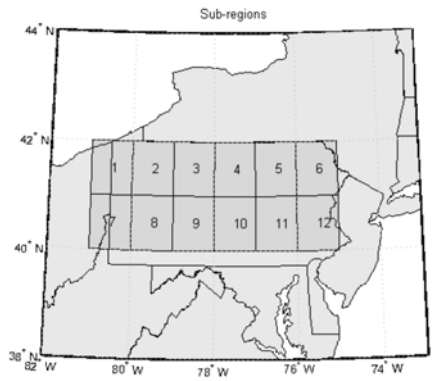


Figure 5.1. Grid used for processing of climate model output and observations.

(1) Annual cycle of mean temperature
(2) Annual cycle of mean precipitation
(3) Annual cycle of interannual temperature variability (standard deviation)
(4) Annual cycle of interannual precipitation variability (standard deviation)
(5) Mean annual cycle of intramonthly temperature variability (std. dev.)
(6) Mean annual cycle of intramonthly precipitation variability (std. dev.)

Table 5.2. Main metrics for the evaluation of climate models.

(1) Maximum number of consecutive dry days within a year*
(2) Maximum 5-day precipitation total within a year
(3) Number of days with precipitation exceeding 10 mm within a year
(4) Fraction of annual precipitation due to top 5 percent of precipitation events (percent)
(5) Growing season length
(6) Number of frost days
(7-11) Maximum number of days per year with the daily maximum temperature greater than 80, 85, 90, 95 and 100 F

Table 5.3. Additional metrics for sectoral applications. Metrics 1-6 are described in detail in Frich et al. (2002). *A dry day is considered to be a day in which precipitation is less than 1 mm.

We computed an overall performance index for each model based on multiple metrics, following the approach of Reichler and Kim (2008). First, an overall squared error was computed for each variable (v, one of the six metrics in Table 5.1) and for each model (m):

$$e_{vm}^2 = \sum_{n=1}^{144} \frac{\left(s_{vmn} - o_{vn}\right)^2}{\sigma_{vn}^2},$$

where n spans all 12 calendar months and 12 grid points within the commonwealth; s_{vmn} represents the simulated metric for each model, month, and grid point; o_{vn} is the corresponding observed metric; and σ_{vn} is the observed interannual variance. e_{vm}^2 was then normalized by its average over all of the models:

$$I_{vm}^2 = \frac{e_{vm}^2}{\overline{e_{vm}^2}^{\,m}}.$$

Finally, the overall performance index was computed by averaging over all of the metrics:

$$I_m^2 = \overline{I_{vm}^2}^{\,v}.$$

Models with an overall performance index less than one are better than average, whereas those with an overall performance index greater than one are worse than average. 95 percent confidence intervals were constructed about the indices using bootstrapping. Bootstrapping was used to generate many (~1000) climatologies, each of which was evaluated with the model data. Once the many indices were calculated, bootstrapping was once again used to generate a 95 percent confidence interval on the index values.

In addition to computing an overall performance index for each model, we also averaged each metric over the state. From this we computed the multi-model mean and standard deviation.

5.4 Results

5.4.1 Model evaluation

Figure 5.2 shows the overall performance index for each model and the model mean based on the first six metrics in Table 5.2. The multi-model mean is significantly (at the 95 percent confidence level) superior to any individual model. In their mid-Atlantic assessment of GCMs from IPCC Third Assessment Report (TAR), Najjar et al. (2008) also found the multi-model mean to be superior to any individual model. At the global

scale, this is a common finding as well (e.g., Lambert & Boer 2001, Reichler & Kim 2008).

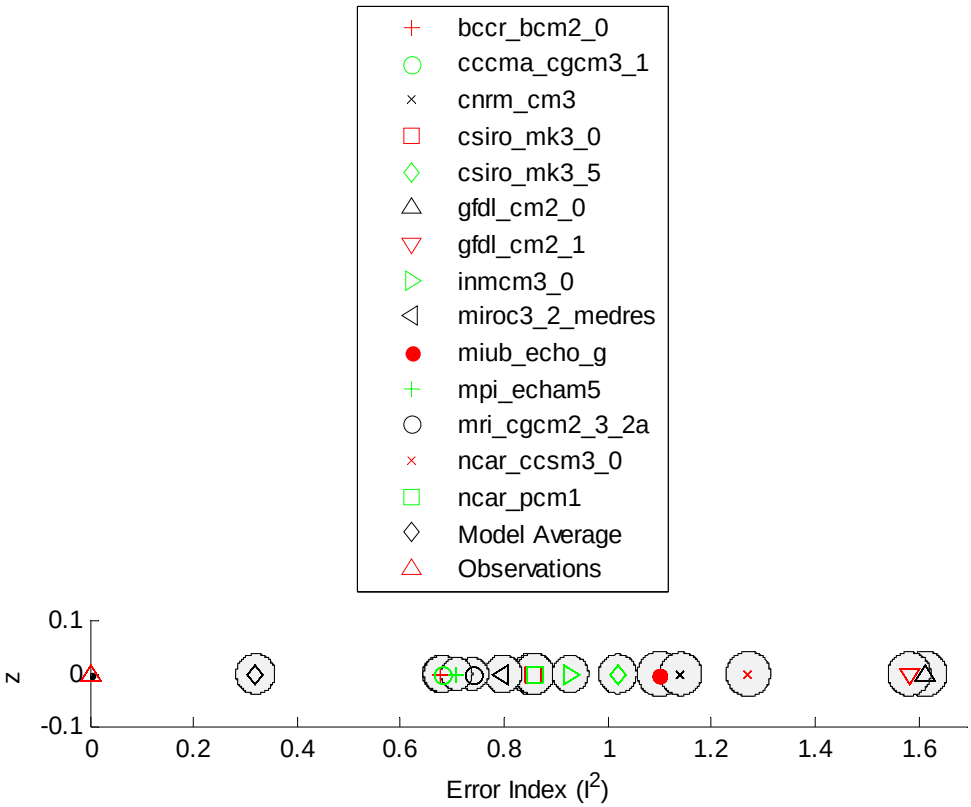


Figure 5.2. Error index for each individual GCM and the multi-model average.

Figure 5.3a shows that the multi-model mean captures the mean annual cycle in Pennsylvania's average temperature very well. There is a very slight cool bias of the models, which is more pronounced in the winter, reaching up to 2 degrees C (4 degrees F). The multi-model mean precipitation is slightly too high (10-20 percent) in all seasons except the summer (Figure 5.3b). Similar biases in the mean annual cycles of mean temperature and precipitation were found by Najjar et al. (2008) in their analysis of models from IPCC's (TAR), but the errors were much larger. Thus, GCMs have improved markedly in their ability to simulate the mean annual cycle of temperature and precipitation in the mid-Atlantic region.

The annual cycle in interannual and intramonthly temperature variability is also captured very well by the multi-model mean, with winter much more variable than summer (Figures 5.4a and 5.5a). For precipitation, the models miss peaks in interannual variability in late spring and early fall (Figure 5.4b). Overall the models have slightly too much interannual variability in temperature and not enough in precipitation. These biases in temperature and precipitation variability were also found by Najjar et al. (2008) in the TAR models, but they are now much reduced in the AR4 models.

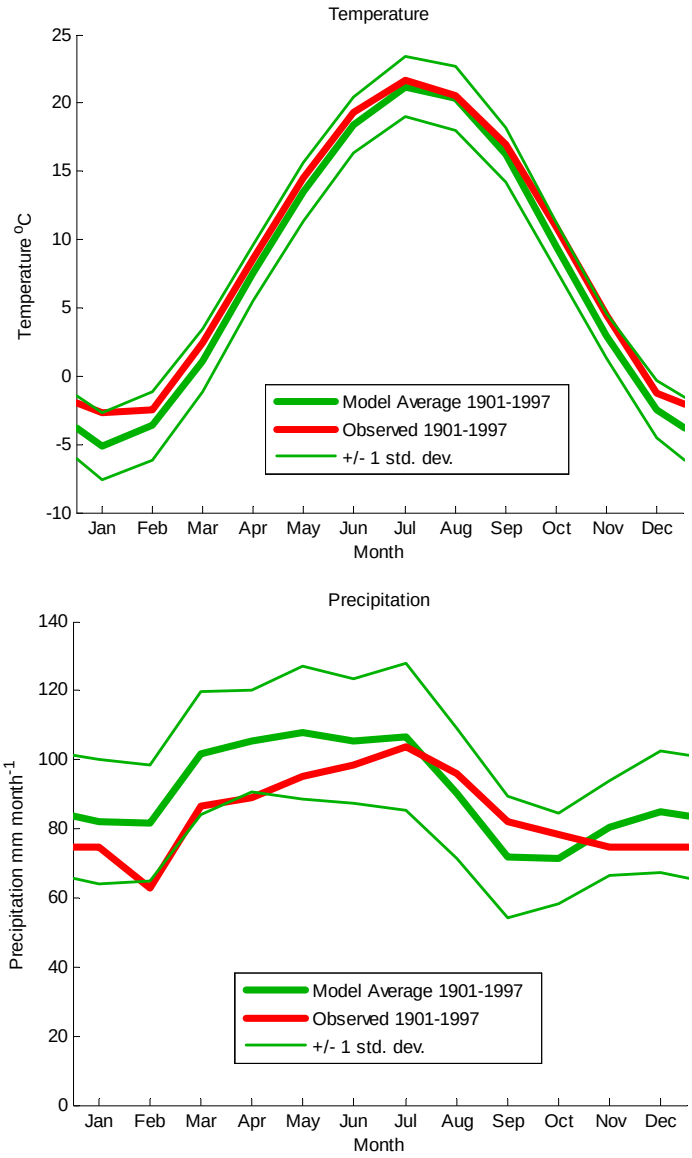


Figure 5.3 a,b. Annual cycle of observed (red) and modeled (green) Pennsylvania-averaged mean temperature (top) and precipitation (bottom).

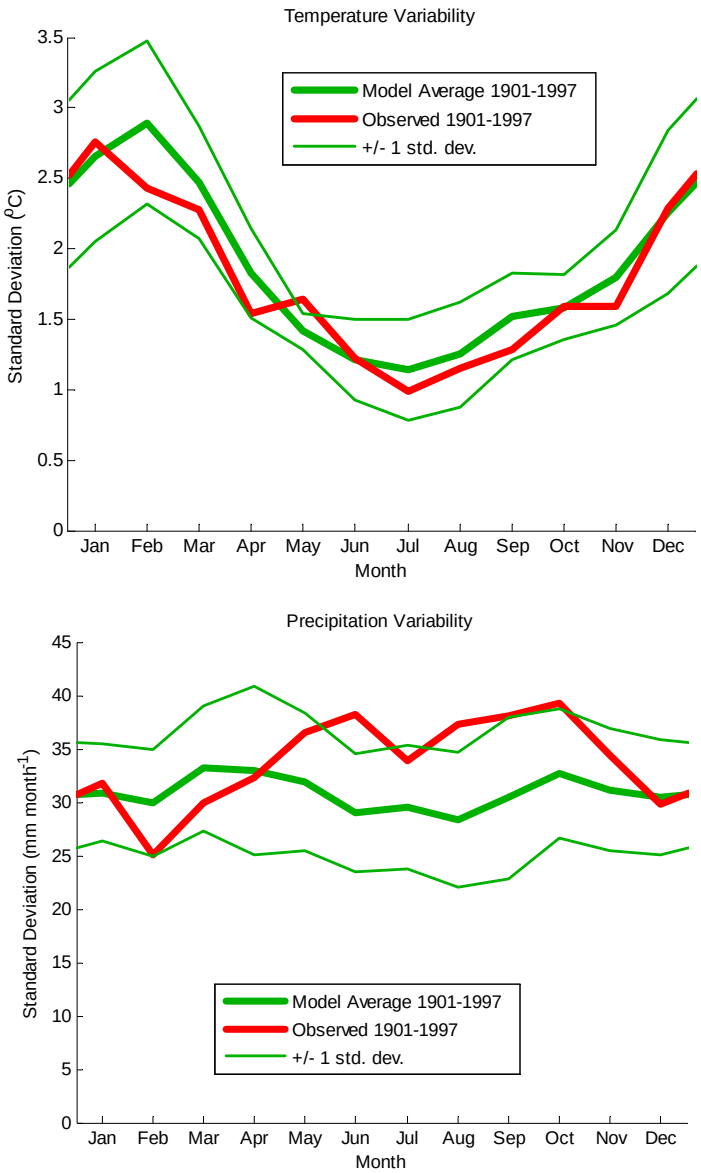


Figure 5.4 a,b. Mean annual cycle of observed (red) and modeled (green) Pennsylvania-averaged interannual variability in temperature (top) and precipitation (bottom).

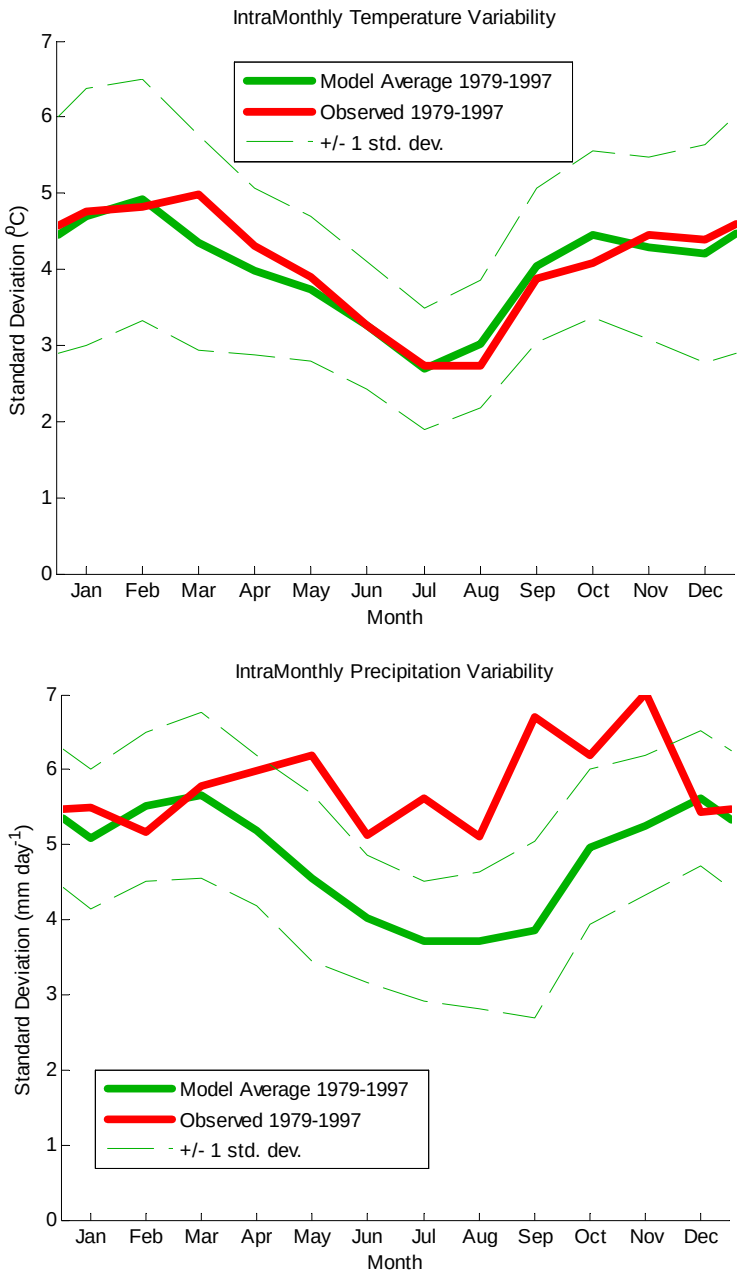


Figure 5.5 a,b. Mean annual cycle of observed (red) and modeled (green) Pennsylvania-averaged intramonthly variability in temperature (top) and precipitation (bottom).

Precipitation, particularly in the summer, is highly localized (due to small-scale convective processes), and hence one would expect GCMs, which have relatively coarse resolution, to underestimate precipitation variability on short time scales. This is indeed the case for all seasons except winter (Figure 5.5b).

Finally, we present an evaluation of the metrics listed in Table 5.3, which include hydrological extremes, agriculture metrics, and extreme heat. In general, the multi-model mean captures the hydrological extremes, with a slight tendency to underestimate them, consistent with the tendency of models to underestimate variability at the submonthly time scale (Figure 5.5b). Differences among models are not dramatic, with the standard deviation typically 15 percent or less. The cool bias of the models in winter (Figure 5.3a) accounts for the overestimation in frost days by about 8 percent, on average. The models tend to overestimate heat waves, which is perhaps related to the tendency of models to have slightly too much temperature variability within a month (Figure 5.5a). More importantly, there is wide range in the ability of the models to capture extreme heat, with the standard deviation typically as large as the mean.

Metric	**Model Average ± 1 standard deviation**	**Observed**
Maximum annual consecutive dry days (days)	31.5 ± 5.3	36.5
Maximum annual consecutive 5-day precipitation total (mm)	63.0 ± 6.4	68.8
Number of days per year with precipitation greater than 10 mm (days)	27.3 ± 3.9	31.0
Fraction of annual precipitation due to top 5 percent of precipitation events (percent)	32.7 ± 4.6	36.7
Number of frost days (days)	123 ± 28	114
Growing season length (days)	182 ± 24	185
Maximum consecutive days in year with daily maximum temperature greater than 80 degrees F, T_{max} > 80 degrees F (days)	12.7 ± 9.2	11.8
T_{max} > 85 degrees F (days)	5.2 ± 4.7	3.7
T_{max} > 90 degrees F (days)	1.6 ± 1.9	0.5
T_{max} > 95 degrees F (days)	0.3 ± 0.6	0.0
T_{max} >100 degrees F (days)	0.1 ± 0.2	0.0

Table 5.4. Model evaluation using metrics for hydrological extremes, agriculture, and extreme temperature.

5.4.2 Projections

We now provide projections of change simulated by the GCMs for three 20-year periods in the 21st century (2011-2030, 2046-2065, and 2080-2099), referenced to a recent 20-year period (1980-1999). As noted earlier (Section 4.2), natural climate variability requires that sufficiently long averages are taken to assess a climate signal. We chose these 20-year intervals to make our results comparable with the IPCC AR4 and many other climate change studies. We present our own analysis of changes in seasonal and annual temperature and precipitation, precipitation extremes, agricultural indices, and extreme heat. We also review the literature on changes in tropical and extratropical storms.

We provide a rough sense of projection error by presenting a distribution of projections among the individual climate models. We used a simple approach to describe the distribution of results by separating the output into quartiles (smallest change, 25th percentile change, median change, 75 percent percentile change, and greatest change). These are conveniently displayed graphically in box-whisker diagrams.

5.4.2.1 Annual and Seasonal Means

Figure 5.6 shows the projected annual temperature and precipitation changes throughout the 21st century for the B1 and A2 emissions scenarios. All 14 models project warming throughout the century regardless of emissions scenario. Despite very different emissions trajectories, there is virtually no difference in the projected climate between the two scenarios over the next 20 years, reflecting the long response time of the climate to CO_2 emissions. By the end of the century, however, the median projected warming according to the A2 scenario is almost 4 degrees C (7 degrees F), which is nearly twice that of the B1 scenario. These differences in climate change between the two emissions scenarios mirror those found at the global scale (Figure 4.7). The full range of projections, regardless of emissions scenario and time period, falls roughly within ±50 percent of the median projection, whereas the middle half of the models falls roughly within ±25 percent of the median projection.

There is less agreement among the models in the projection of precipitation change compared to that of temperature change. However, most models (>3/4) project increases in precipitation regardless of time period and emissions scenario. By late century, the median A2 precipitation projection is a 10 percent increase with more than half of the models falling between increases of 3 to 12 percent.

The projections differ seasonally, with greater warming projected in the summer and greater precipitation projected in the winter (Figures 5.7 and 5.8). There is also greater agreement among the models (for both temperature and precipitation) in winter as compared to summer (see also Figure 4.5), which may reflect the difficulty in the GCMs capturing the smaller-scale convective events, which are more important in the summer.

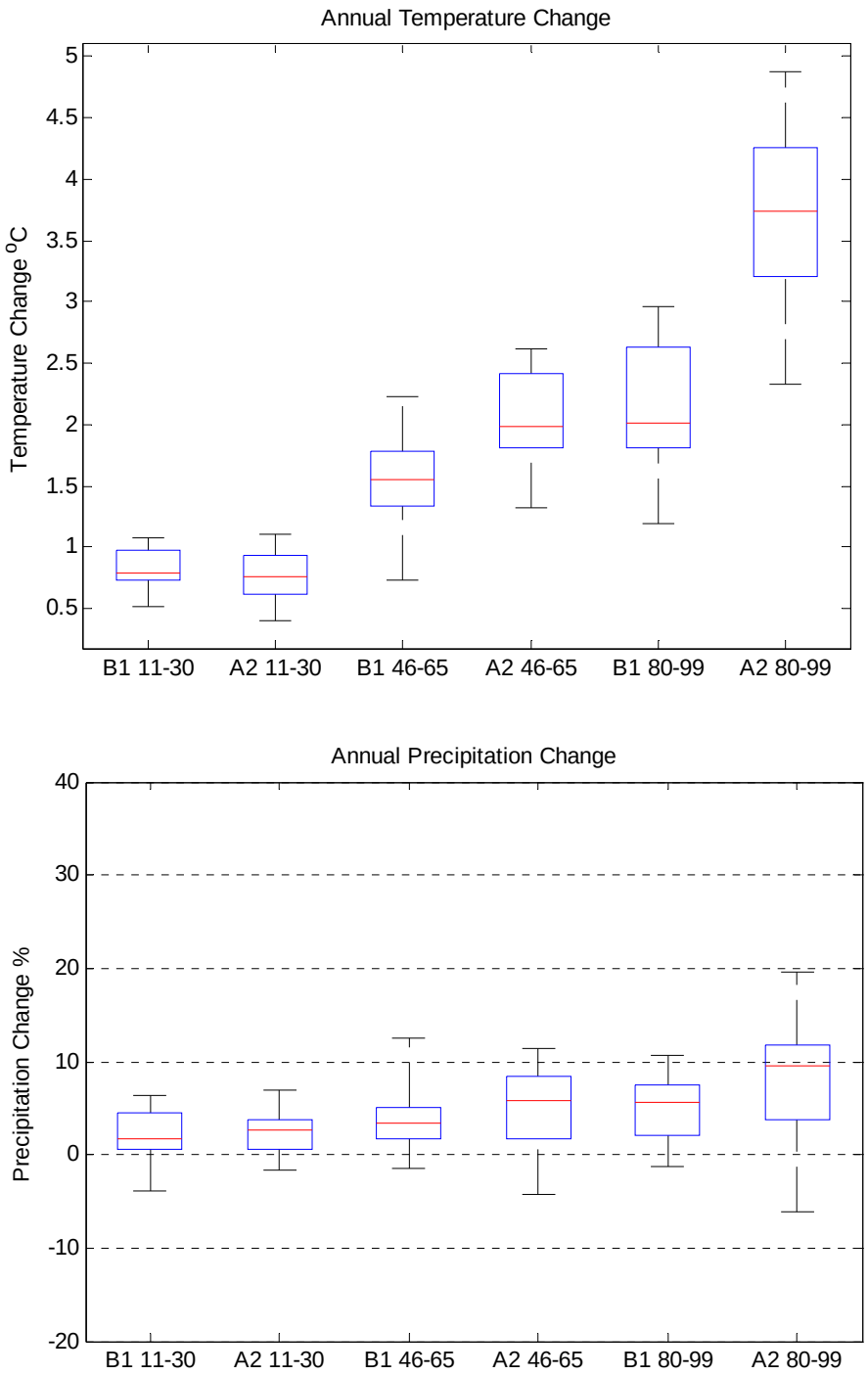


Figure 5.6 a,b. Box-and-whisker plots of annual mean changes in temperature (top) and precipitation (bottom) for three future time periods (2011-2030, 2046-2065, and 2080-2099, all compared with 1980-1999) and two emissions scenarios (B1 and A2). The plot shows the median projection (red line), the 25th to 75th percentile projections (blue box), and the maximum and minimum projections (black lines).

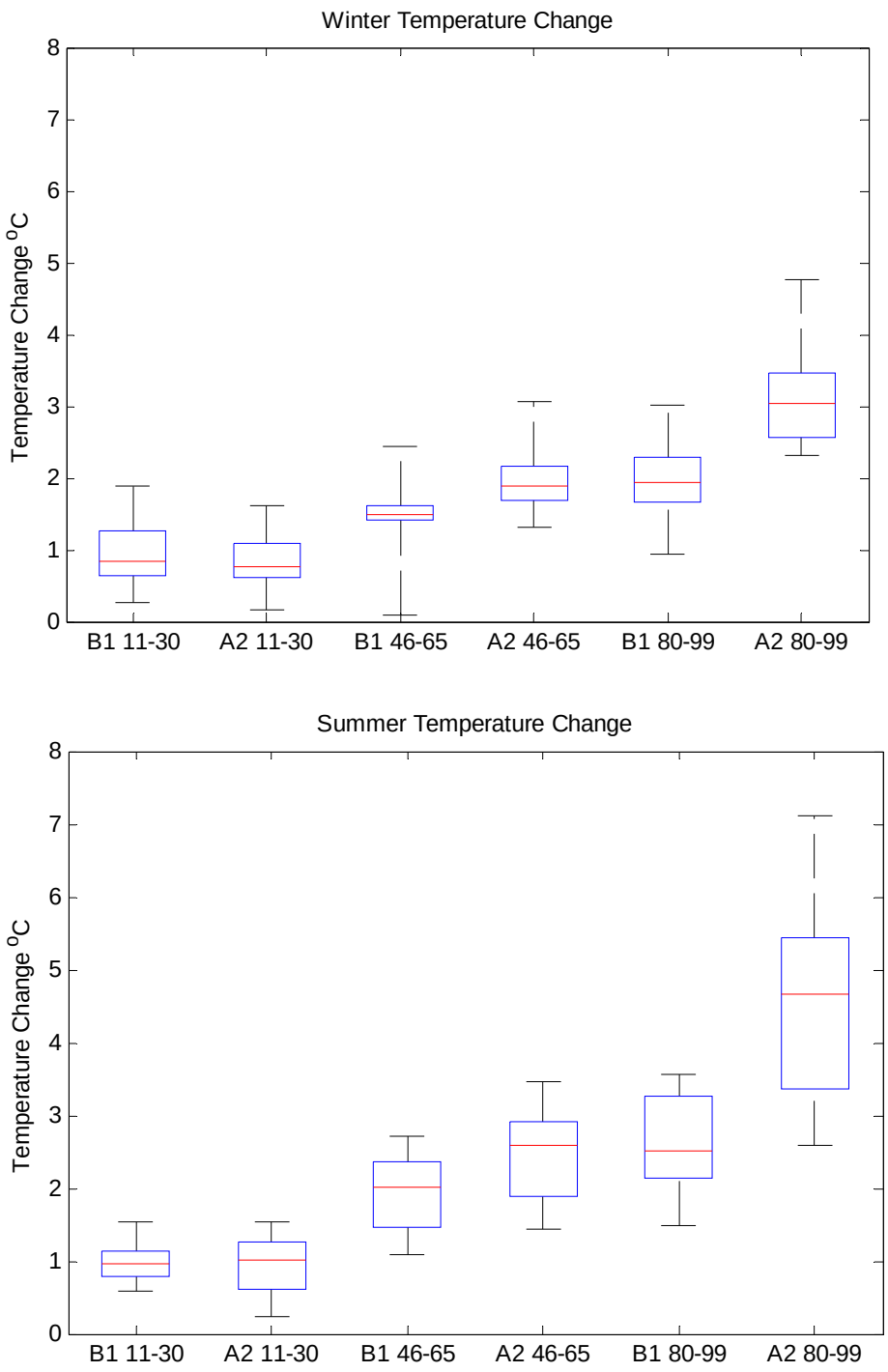


Figure 5.7 a,b. Same as Figure 5.6, except for winter (top) and summer (bottom) temperature change.

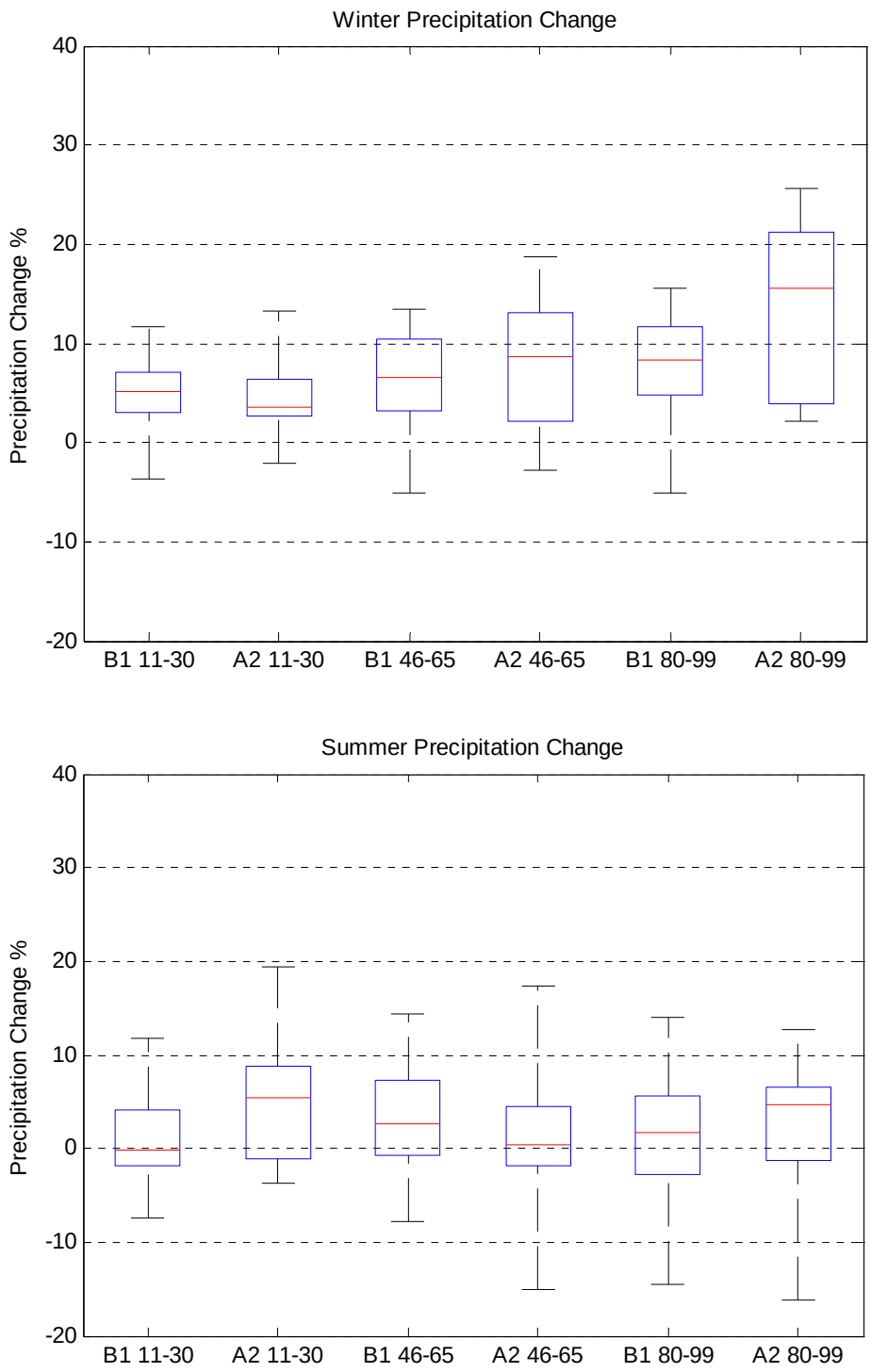
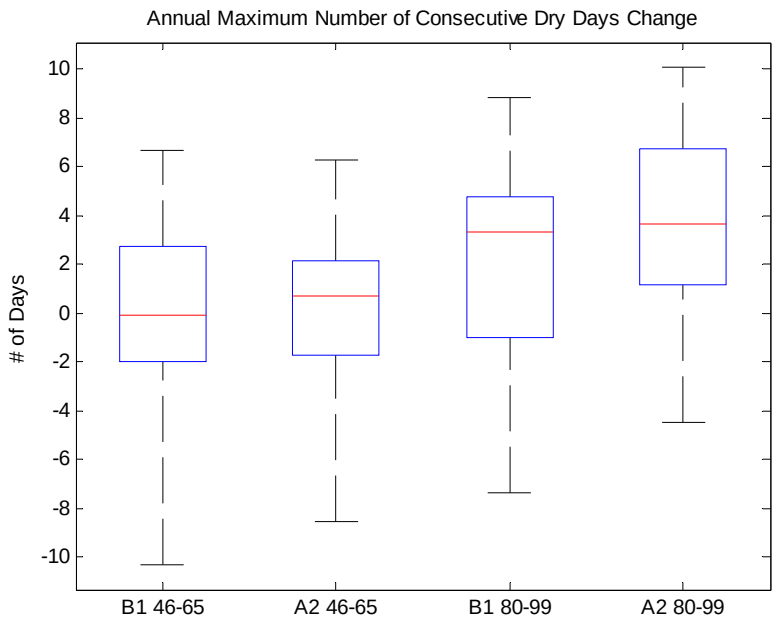


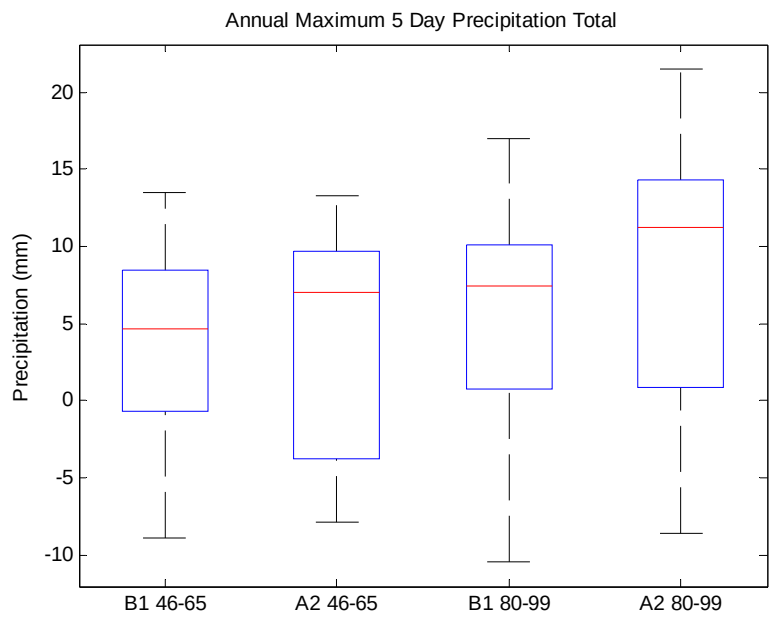
Figure 5.8 a,b. Same as Figure 5.6, except for winter (top) and summer (bottom) precipitation change.

Though we do not have model simulations available to us for the most extreme IPCC emissions scenario, A1FI, we can estimate the projected Pennsylvania climate for this scenario based on projected global temperatures, as described by Najjar et al. (2008). Compared to the A2 scenario, projected increases for the A1FI scenario should be increased by roughly 10 percent for early century, 30 percent for mid-century, and 25 percent for late century. Thus, for example, the median projected summer temperature increase for the A1FI scenario by late century would be the corresponding A2 projection (4.8 degrees C or 8.6 degrees F) multiplied by 1.25, which is equal to 6.0 degrees C (11 degrees F). This agrees well with the late-century summer projection of Pennsylvania temperature change by the Union of Concerned Scientists (2008).

5.4.2.2 Precipitation Extremes

Figure 5.9 shows how extremes in precipitation are projected to change by mid- and late-21st century. The maximum number of consecutive dry days in a year, a drought indicator, is projected to increase for most time periods, scenarios, and models throughout the 21st century. Median projections are increases of 1 day by mid-century and up to 4 days by late century under the A2 scenario above the baseline value of 31.5 days (Table 5.4). The annual maximum 5-day precipitation total averages 63 mm in the baseline period (multi-model mean), and increases by 11 mm (median projection) for the A2 scenario by late century. The number of days in a year with precipitation exceeding 10 mm increases slightly by 5-6 days (median) throughout the 21st century above the baseline simulation of 27 days. Finally, the fraction of annual precipitation that arrives in daily events that exceed the historical 95th percentile of events is simulated to be 33 percent for the baseline period (multi-model mean), and this increases up to 40 percent for the A2 scenario by late century (median projection). In summary, most models (about 3/4) suggest that Pennsylvania's precipitation climate is projected to become more extreme in the future, with longer dry periods and greater intensity of precipitation.


Annual Maximum Number of Consecutive Dry Days Change
# of Days
10
8
6
4
2
0
-2
-4
-6
-8
-10
B1 46-65
A2 46-65
B1 80-99
A2 80-99


Annual Maximum 5 Day Precipitation Total
Precipitation (mm)
20
15
10
5
0
-5
-10
B1 46-65
A2 46-65
B1 80-99
A2 80-99

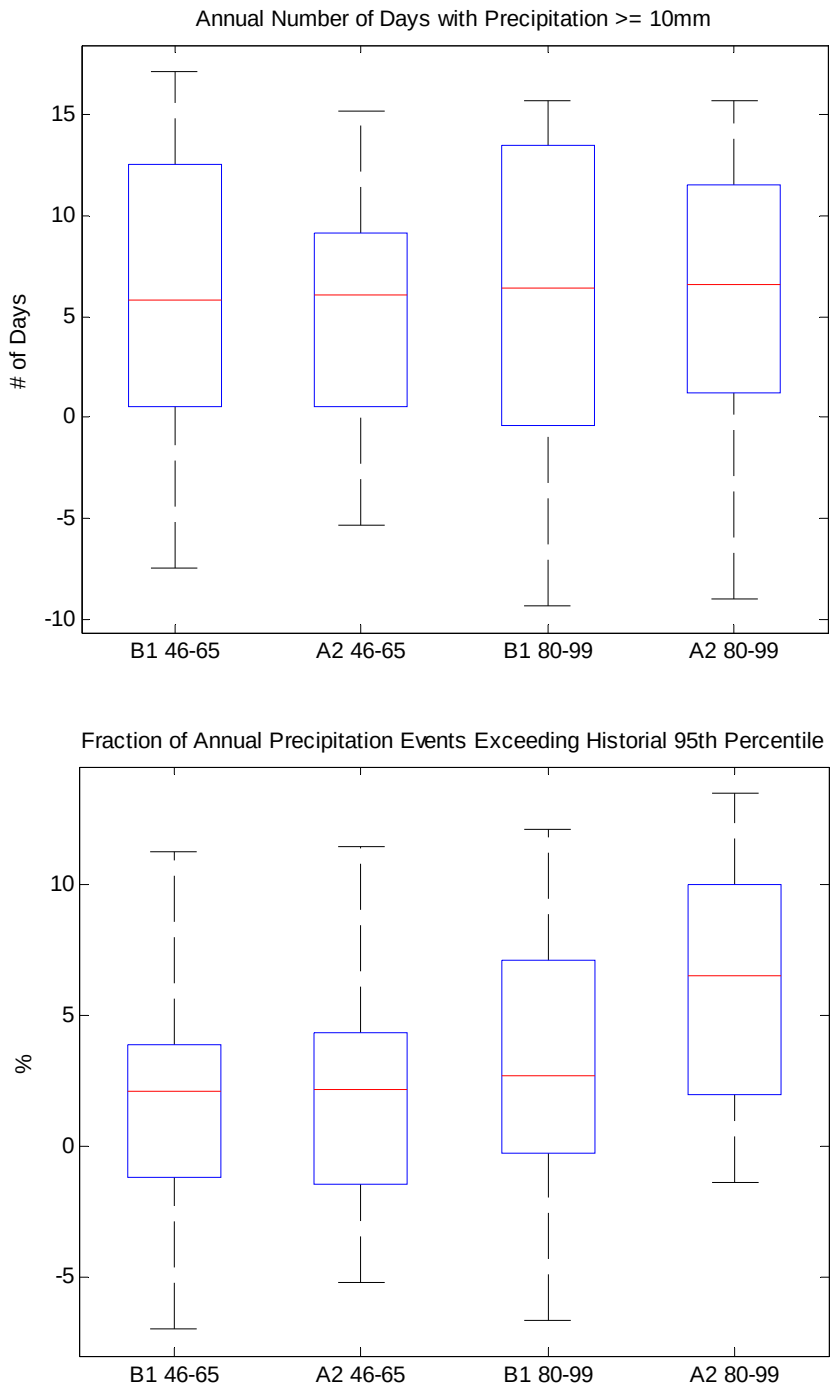


Figure 5.9 a-d. Box-and-whisker plots of changes in the four metrics of precipitation extremes for two future time periods (2046-2065, and 2080-2099, all compared with 1980-1999) and two emissions scenarios (B1 and A2). The metrics are: (a) maximum consecutive dry days, (b) maximum 5-day precipitation total, (c) number of days with precipitation above 10 mm, and (d) the fraction of annual precipitation that occurs in daily events exceeding the historical 95th percentile.

5.4.2.3 Agricultural Indices

Important climate indices for agriculture include the length of the growing season and the frequency of frosts. Figure 5.10 presents projected changes in the Pennsylvania-averaged growing season length and number of frost days per year by mid- and late-21st century for the B1 and A2 scenarios. These indices are defined following Frich et al. (2002). The results show clear increases in growing season length, with median projections of almost a 3-5 week lengthening by late century, depending on the scenario. Corresponding frost day decreases are almost 4-6 weeks.

5.4.2.4. Extreme summer heat

Figure 5.11 shows the projected change in the average number of days per year that the state-averaged high temperature exceeds 80 degrees F and 90 degrees F. For the baseline simulation (late 20th century), the model mean is less than 2 weeks per year above 80 degrees F. By late 21st century, based on the median projection, days above 80 degrees F double (B1 scenario) to more than triple (A2 scenario) compared to the late 20th century. An even greater sensitivity is found for the number of days above 90 degrees F, with the B1 and A2 scenarios by late century projecting an increase of 3 and 10 days, respectively, above the late 20th century simulated value of 1.6 days. For comparison, The Union of Concerned Scientists (UCS, 2008) found that the number of days above 90 degrees F increased by 15 to 25 days (depending on location) for the B1 scenario by late 21st century compared to late 20th century. This appears to be a substantially larger increase than we find. The difference may be a result of any of the following factors, individually or in combination: (1) the different models used (3 models were used by UCS compared to the 14 presented here), (2) that our metric is state-averaged compared to city-specific projections by the UCS, and (3) downscaling by the UCS compared to simple interpolation used here. The difference does not seem to be related to projections in mean temperature, which are similar to ours (Section 5.4.2.1). A similar discrepancy is found for days above 100 degrees F: we find an increase of 1 day (median projection) by late century under the B1 scenario (not shown), compared to nearly a week found by the UCS.

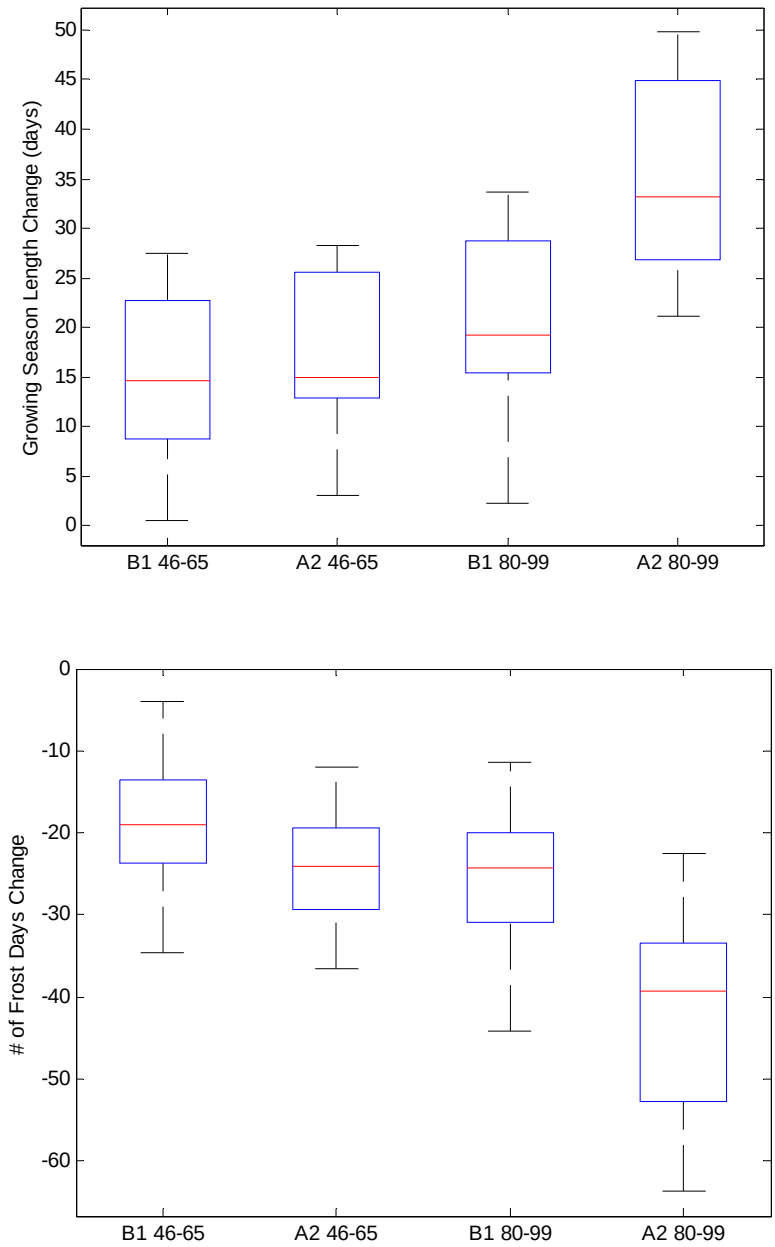


Figure 5.10 a,b. Same as Figure 5.9 except for growing season length (top) and number of frost days (bottom).

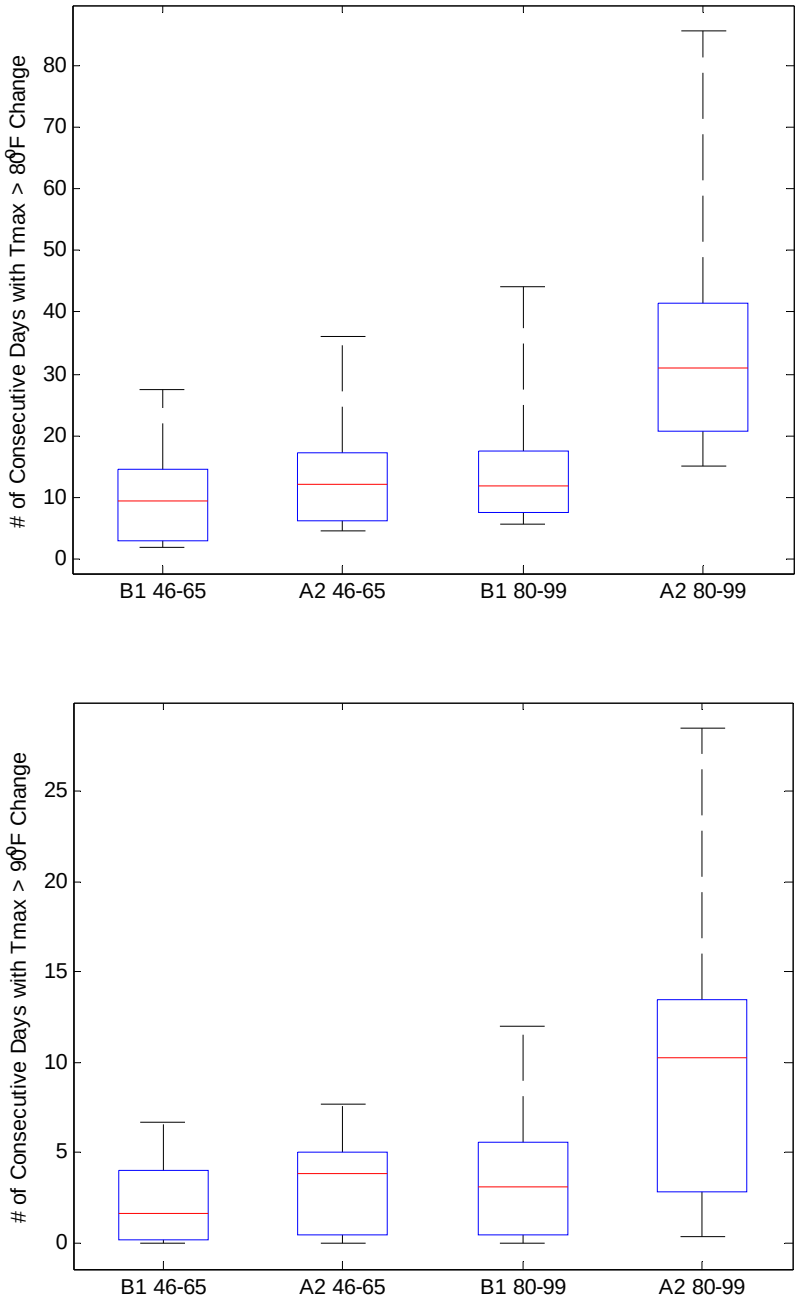


Figure 5.11 a,b. Same as Figure 5.9 except for growing season length (top) and number of frost days (bottom).

5.4.2.5 Storm Frequency and Intensity

Pennsylvania experiences impacts from storms in all seasons. Here we consider the published literature on projected changes in tropical and extratropical storms that could impact the Commonwealth.

Tropical Storms

Since the 1970s there has been an upward trend globally in tropical cyclone destructiveness (as measured by the Power Dissipation Index, PDI), resulting from increases in intensity and duration, which is correlated with sea surface temperature (see summary by Trenberth et al. [2007]). This suggests that future warming of the tropical ocean surface, which is consistently projected by GCMs, will lead to future increases in tropical cyclone destructiveness. Indeed, syntheses of future projections made by Christensen et al. (2007) and Meehl et al. (2007) suggest that peak wind speeds in tropical cyclones will increase over the 21st century. However, more recent studies suggest such increases will be minor. Knutson et al. (2008) forced a high resolution numerical model for the Atlantic basin with a multi-GCM mean change in climate by late century under the A1B scenario. They found an 18 percent decrease in hurricane frequency and a slight increase in intensity; the PDI decreased by 25 percent. Emmanuel et al. (2008) simulated tropical cyclone changes by using a novel approach in which GCMs are randomly seeded with tropical cyclones, the development of which depends on large-scale conditions simulated by the GCM. For the Atlantic basin, they found results that varied substantially among GCMs. The multi-model average yielded a 2 percent increase in frequency, a 7 percent increase in intensity, and a PDI increase of 10 percent.

Winter Storms

The location of mid-latitude (extra-tropical) low pressure systems and their movement across the surface is controlled by the upper tropospheric circulation. This circulation is, to some degree, anchored by the distribution of oceans and continents and by topography. Over the U.S., the Rocky Mountains tend to produce a ridge in the upper atmospheric flow, with a downstream trough over the eastern part of the continent. The strength of the trough (how far southward it extends) and its east-west displacement can vary considerably over time scales of a few days. The prevalence of a particular pattern within the season also varies considerably from year to year and has a major impact on the frequency and intensity of storms passing over Pennsylvania. This basic system over North America is unlikely to change in any significant way with global warming, although particular flow patterns could become more or less frequent.

Recent analyses for the Northern Hemisphere based on the IPCC models suggest a decrease in frequency and an increase in intensity of extratropical winter cyclones with no significant change in the storm track (Lambert and Fyfe, 2006). Using the multi-model IPCC data but a different methodology, Ulbrich et al. (2008) also find an increase in storm activity in the eastern North Pacific and North Atlantic Oceans, but with some evidence of a northward displacement of the storm track in both regions. There is some

indication of a slight decrease in activity over the Great Lakes, but little indication of a change in activity or location of the storm track over Pennsylvania and the mid-Atlantic region. Taken with the precipitation projections that indicate fewer but more intense precipitation events, this suggests that the frequency and intensity of storms may change, but winter storms will continue to pass over Pennsylvania in the future much as they do today.

Major ice storms (such as the storm that hit Pennsylvania in December 2008) and significant rain-on-snow flooding develop as a response to particular sequences of weather events. How these are likely to change in the future can not be determined without a more detailed downscaled analysis of the daily sequences of synoptic events projected by GCMs. However, the relative stability of the storm track, together with the projection of somewhat wetter winters, would suggest that lake-effect snow will continue to be an issue in the northwest part of the State. At the same time, while there will be considerable variability across the State (as there is now), the wetter and milder conditions may increase the potential for systems bringing more mixed snow/ice/rain events. This also indicates that while late 21st-century temperatures in Pennsylvania may be analogous to those of present day North Carolina or Georgia, it would be a mistake to take the analogy too far. The difference in geographic location (i.e. the proximity of the Great Lakes and Pennsylvania's location with respect to North American storm tracks) means that Pennsylvania's winters in the future will be different to any analogues we might suggest from today.

5.5 Summary

General Circulation Models are useful tools for projecting the climate impacts of greenhouse gas emissions. Though the coarse resolution of GCMs has traditionally discouraged their use in regional climate change impact assessments, such as this one, improvements with time in these models (including finer resolution) has made them increasingly viable tools at the regional scale. Important and active areas of research are the development of (1) statistically rigorous error estimates for GCM projections at the regional scale, and (2) techniques for downscaling regional climate output to the local scale (such as for an individual city). We did not have the resources to apply these techniques to Pennsylvania, though we were able to provide an overall assessment of model reliability for the climate averaged over the Commonwealth. Our overall findings for climate model evaluation based on a variety of metrics based on surface temperature and precipitation, are:

- Individual GCMs differ dramatically in their ability to simulate the climate of Pennsylvania.
- The multi-model mean produced a credible simulation of Pennsylvania's recent climate, superior to the simulation of any individual GCM.
- The multi-model mean is slightly too cool and wet, and is slightly muted in its variability on sub-monthly time scales.
- From submonthly to interannual time scales, the multi-model mean captures variability in temperature and precipitation reasonably well.

The credible simulation of Pennsylvania's past climate means that GCM projections for the region can provide useful information for the impacts of projected climate change. The spread in individual GCM results provides a rough estimate of the GCM error. Our main findings for the projected climate of the Commonwealth are:

- It is very likely that Pennsylvania will warm throughout the 21st century; not a single GCM simulates cooling under two different emissions scenarios.
- It is likely that annual precipitation will increase in Pennsylvania and very likely that winter precipitation will increase.
- Projected climate change for the Commonwealth is independent of emissions scenario over the next 20 years and becomes substantially dependent on emissions scenario by late century.
- By the end of the century, the median projected warming according to the A2 scenario is almost 4 degrees C (7 degrees F), which is nearly twice that of the B1 scenario.
- By late century, the median B1 and A2 annual precipitation projections are 6 and 10 percent, respectively. Corresponding winter projections are 8 and 15 percent.
- Warming will lead to a longer growing season, with median B1 and A2 projections of nearly 3 and 5 weeks lengthening, respectively, by late century. Corresponding frost day decreases are nearly 4 and 6 weeks.
- It is likely that Pennsylvania's precipitation climate will become more extreme in the future, with longer dry periods and greater intensity of precipitation.
- There is substantial uncertainty in projections of future tropical and extratropical cyclones for Pennsylvania. Current research suggests fewer storms but with increases in intensity.

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6.0 Water Resources

6.1 Introduction

Rising greenhouse gas emissions are leading to an unequivocal warming of our climate system with observed increases in air and ocean temperatures, melting of snow and ice and rising sea levels (Bernstein et al., 2007). This non-stationarity in our climate system has significant implications for the global hydrological cycle with "*changes in all components of the freshwater system*" (Kundzewicz et al., 2007). It will impact the distribution, availability, timing, quality, demand of freshwater resources across our planet. Precipitation patterns, as reflected in the amount, intensity, frequency, and type of precipitation have already changed significantly over the last 100 years (Trenberth et al., 2007; Cook et al., 2008). In general, higher temperatures will likely lead to an intensification of the hydrological cycle, though with significant regional variability. We have already seen an increase in extreme hydrological events, including droughts, hurricanes and floods (Trenberth et al., 2007; Trapp et al., 2009). In this section, the implications of climate change on water resources will be discussed while moving from global to regional scale. The above mentioned global changes will have significant implications for water management, which until recently, relied heavily on historical hydrological observations and the assumption of stationarity (see Colley, 2009; Milly et al., 2008). However, "*the socioeconomic impacts of floods, droughts, and climate and non-climate factors affecting the supply and demand for water will depend in large part on how society adapts*" (Frederick and Gleick, 1999). A recently published world water assessment report by United Nations Educational Scientific and Cultural Organization concludes that: "*The main impacts of climate change on humans and the environment occur through water"* and that "*The world is facing global crises in energy, food, and climate change and global warming that cannot adequately be addressed without considering the role of water"* (World Water Assessment Programme, 2009).

Observed U.S.- and Pennsylvania-wide trends in changes to the hydrological cycle over the last century are shown in Table 6.1. Overall, climate change implications will likely further constrain already over-allocated North American water resources and thus increase the competition between agricultural, municipal, industrial and ecological demands (Bates et al., 2008). The actual implications will vary widely throughout the USA with the southwestern and western U.S. becoming major climate impact hotspots (Diffenbaugh et al., 2008). For example, current projections suggest a decrease of precipitation in the southwestern U.S., while the remainder of the nation is more likely to see an increase. Overall, the recent IPCC report suggests greater changes in precipitation extremes than in its averages (Bates et al., 2008). A widespread consequence of global warming is the alteration of the type, amount and timing of precipitation, potentially leading to earlier snowmelt and general reductions in snow cover, as well as to a lengthening of the growing season (Barnett et al., 2008). Other implications of climate change will be harder to project due to the complex interaction of multiple controlling factors. Groundwater, for example, depends on changes to withdrawals, land cover, evapotranspiration and recharge – thus making it harder to make general projections of the development of this resource across the U.S. Coastal aquifers, however are likely to

see an increase in saltwater intrusion due to sea level rise and land subsidence especially at the Gulf Coast (Bates et al., 2008)

6.2 Historical Climate and Hydrology of Pennsylvania

Pennsylvania is a temperate region with a river drainage network that is defined by a large number of small perennial streams (Sankarasubramanian and Vogel, 2003; Freeman et al., 2007). Precipitation is distributed relatively uniformly throughout the year with little differences between monthly average amounts. The distribution of temperature on the other hand shows a strong seasonal trend with a summer peak. Potential evapotranspiration follows the same distribution. Streamflow distribution throughout the year is related to evapotranspiration amounts and the relative occurrence of precipitation as rain or snow. Spring snowmelt events, in particular rain on snow events, will generally produce the largest streamflow. Precipitation in Pennsylvania predominantly falls as rainfall with snow only accounting for 10 to 25 percent (depending on the location within Pennsylvania) of the total annual precipitation on average. Precipitation itself is also quite variable across the state, but averages slightly over 40 inches per year. The part of the precipitation that falls during the growing season is returned almost completely to the atmosphere as evapotranspiration – about 21 inches on average. Of the remaining precipitation, about 7 inches produce runoff relatively quickly while the rest (13 inches) recharges the groundwater. *Most of this recharge occurs from rain and melting snow during early spring and late fall when the soil is not frozen and plants are not actively growing* (Swistock, 2007). Pennsylvania's mainly perennial streams typically receive two-thirds of their flow from groundwater. Groundwater aquifers in Pennsylvania can sometimes be found only a few feet below the surface, but most often are at depths greater than 100 feet. These aquifers provide a great freshwater resource though the use of this resource (mainly for water supply) has remained relatively constant over the last few decades (Swistock, 2007).

Pennsylvania's climate, and therefore its hydrology, has already seen significant changes over the last century, thus providing an indication of potential future changes (Table 6.1). The last 100 years have seen an increase in annual temperatures (by over 0.5 degrees F) and in annual precipitation in most of the state (UCS, 2008). Annual air temperatures have risen over the North-East in general (+0.08 +/- 0.01 degrees C/decade), especially since about 1970 where rates have been even higher (+0.25 +/- 0.01 degrees C/decade) (Hayhoe et al., 2007; Huntington et al., 2009). Warming was higher during the winter periods, thus leading to a decrease in snow cover and an earlier arrival of spring. Precipitation has also increased over the last century, with additional amounts ranging between 5 and 20 percent throughout the state (UCS, 2008). This additional moisture falls in the winter months, while summers have actually seen a slight decrease in precipitation. Average annual precipitation increased from 38 inches to 44 inches throughout the twenty-first century (UCS, 2008). Soil-moisture-related droughts have also increased due to increased summer temperatures and decreased rainfall. Simulations of the hydrology of the northeastern US over a 50 year period (1950 to 2000) suggest a decline in available soil moisture during the period from June to August over large areas (Sheffield and Wood, 2008). This decline is most likely mainly caused by an increase in

evapotranspiration during the summer period since rainfall amounts remained relatively stable over the same period. *Historically, short-term droughts* (lasting one to three months) *occurred roughly once every three years over western Pennsylvania and once every two years over eastern Pennsylvania. Medium-term droughts* (lasting three to six months) *are far less common in Pennsylvania; they have occurred once every 10 years in western parts of the state and rarely in most eastern areas. Long-term droughts* (lasting more than six months) *have occurred on average less than once in 30 years* (UCS, 2008). Annual streamflow has also increased, but to a lesser degree. Milly et al. (2005) calculated that runoff (streamflow) across the northeastern U.S. has increased between 0 to 5 percent using GCM projections for the 20th century. McCabe and Wolock (2002) found that this increase was mainly in the lower and intermediate flow quantiles for New England and the mid-Atlantic regions.

Water resource change	IPCC examples for North America (AR4)		PA	
1-4 week earlier peak streamflow due to earlier warming-driven snowmelt	↑	U.S. West and US New England regions	↑	Increase in growing season length
Proportion of precipitation falling as snow	↓	U.S. West	↓	Decline
Duration and extend of snow cover	↓	Most of North America	↓	Decline
Annual precipitation	↑	Most of North America	↑	Up in winter months, constant in summer months. Overall increase
Frequency of heavy precipitation events	↑	Most of U.S.	↑	Increase in heavy precipitation
Streamflow	↑	Most of the Eastern U.S.	↑	Overall increase, but lower in summer and fall
Water temperatures of lakes (0.1degrees -1.5 degrees C)	↑	Most of North America	↑	Increase
Salinization of coastal surface waters		Florida, Louisiana		Delaware Estuary
Periods of droughts	↑	Western U.S.	↑	Increase of both soil moisture related droughts and decrease in summer / fall low flows

Table 6.1. Observed changes to North American Water Resources during the 20th century (North America examples from Bates et al., 2008, p.102). Pennsylvania trends are generally typical for the Northern U.S.

6.3 Climate Change Implications for the Water Cycle in Pennsylvania

The complexity of the hydrological cycle with nonlinearities, thresholds and feedbacks makes it hard to model potential future conditions of variables such as soil moisture and streamflow with high reliability. This is particularly true considering the uncertainty already present in the projections of the meteorological drivers (i.e. precipitation and temperature). One can probably have high confidence in General Circulation Model projections of temperature, moderate confidence in temperature extremes, moderate confidence in precipitation and low confidence in precipitation extremes. This likely translates into moderate confidence in the directional change of hydrological variables and lower confidence in estimates of extreme conditions as discussed in more detail below.

6.3.1 Precipitation – Rainfall and Snow

A detailed discussion of past and future climatic conditions in Pennsylvania can be found in section 5. This discussion is reiterated here as far as it necessary to support the assessment of the Pennsylvania water cycle under climate change conditions. For Pennsylvania, more than three-quarters of all GCMs analyzed project an increase in annual precipitation throughout the 21st century regardless of scenario analyzed (Figure 5.6b). Most of this precipitation increase is projected to occur in the winter months (Figure 5.8). The uncertainty of precipitation estimates for the summer is likely to be higher as reflected in reduced model agreement during this part of the year. All 21 GCMs analyzed in section 5 simulate increasing temperatures for Pennsylvania throughout the 21st century regardless of emission scenario analyzed. Warming projections reach about 4 degrees C for the A2 scenario by the end of the century, while the B1 scenario reaches about half of this value. This trend suggests that an increasing fraction of precipitation will fall in liquid form, rather than as snow, which is consistent with historical trends observed over the last 30 years in the region (Huntington et al., 2004). Hydrological modeling studies – necessary due to a lack of historical snow observations – using historical precipitation and temperature data between 1970 and 1999 suggest statistically significant trends for decreasing snow water equivalent (about -3 mm/decade) and for decreasing numbers of snow-covered days (about -0.5 days/month/decade) (Hayhoe et al., 2007, Fig. 6.1). Snow-covered days are defined in Hayhoe et al. (2007) as those days with a snow water equivalent larger than 5 mm. Overall, Pennsylvania's precipitation regime is projected to become more extreme, including longer dry periods and greater intensity of precipitation events (Figure 5.9). Increases in intense precipitation have already been observed for Pennsylvania (Madsen and Figdor, 2007). The order of magnitude of change and the direction of change are consistent with other climate change impact studies for the northeastern US (e.g. Hayhoe et al., 2007; UCS, 2008).

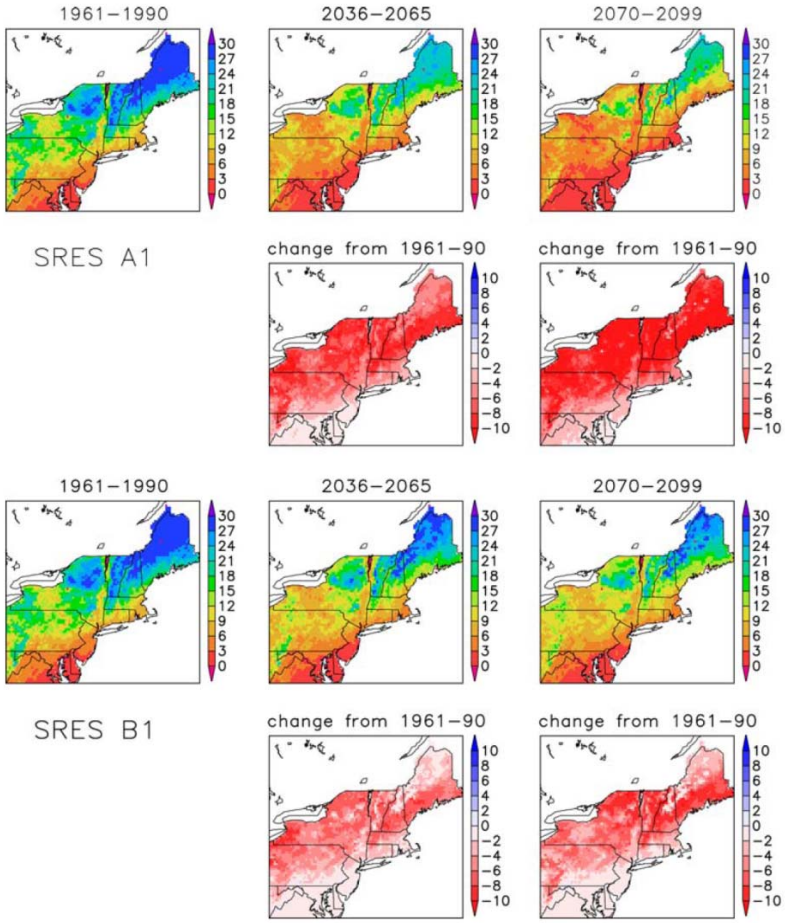

Figure 6.1. Results of HadCM3 and PCM GCM-output driven simulations with the VIC land-surface model. Plots show snow-covered days per month from December to February averaged over 30-year periods. 'Change' refers to the difference between period 1961-1990 and future periods. (Figure from Hayhoe et al., 2007).

6.3.2 Evapotranspiration

Evapotranspiration is the combined process of evaporation from the soil surface and open water bodies and transpiration from vegetation. The fraction of precipitation that evapotranspires is no longer available as freshwater supply for further use. GCM projections generally suggest an increase in potential evapotranspiration due to increased temperatures throughout the year for both emission scenarios. Increasing moisture availability, at least in the beginning of the summer, should also lead to increased actual evapotranspiration. Evapotranspiration is generally lower in the winter and is likely to decrease further with a decreasing snow pack and hence reduced sublimation (Hayhoe et al., 2007). The expected lengthening of the growing season (earlier spring and later fall, see Figure 5.10a) is likely to result in an additional increase in actual evapotranspiration. Such a lengthening of the growing season has already been observed for the study region and beyond (Christidis et al., 2007).

6.3.3 Streamflow/Runoff

Climate change impact studies performed so far generally suggest a slight increase in runoff across the northeastern U.S. (Milly et al., 2005) across all emission scenarios, though with variability in the projections of different climate models (Fig. 6.2). As a first order estimate of runoff, one can assume that, over a multi-year period, the average runoff is equal to the difference between precipitation and evapotranspiration (assuming no storage change), and thus to the convergence of atmospheric moisture flux (Milly et al., 2005). Sankarasubramanian and Vogel (2003) calculated a precipitation elasticity of streamflow across the northeastern U.S. between 1.5 and 2.5 for most areas based on an analysis of almost 1400 watersheds across the U.S. Elasticity is an index describing the proportional change in streamflow to the proportional change in precipitation. This means that they suggest that for a 1 percent change in precipitation, streamflow will change by 1.5 to 2.5 percent. The non-linearity in this relationship is a function of storage processes within the watershed. The overall increase in precipitation projected is thus likely to result in a slight increase in runoff. Hayhoe et al. (2007) drive a large-scale hydrological model (VIC) with GCM output (precipitation and temperature) for both a historical period (50 years) and for future projections over the northeastern U.S. (see also Fig. 6.1). Their results show slight changes in runoff over the historical period, but none of them statistically significant in strength. Future projections show wetter winters and generally higher temperatures, leading to an overall increase in runoff in the order of 5 percent (Fig. 6.2). This runoff increase will likely be in the winter months though, and peak runoff is projected to occur earlier in the year. Implications of climate change on annual runoff might also be smaller in watersheds that are (or will be) more urbanized (DeWalle et al., 2000).

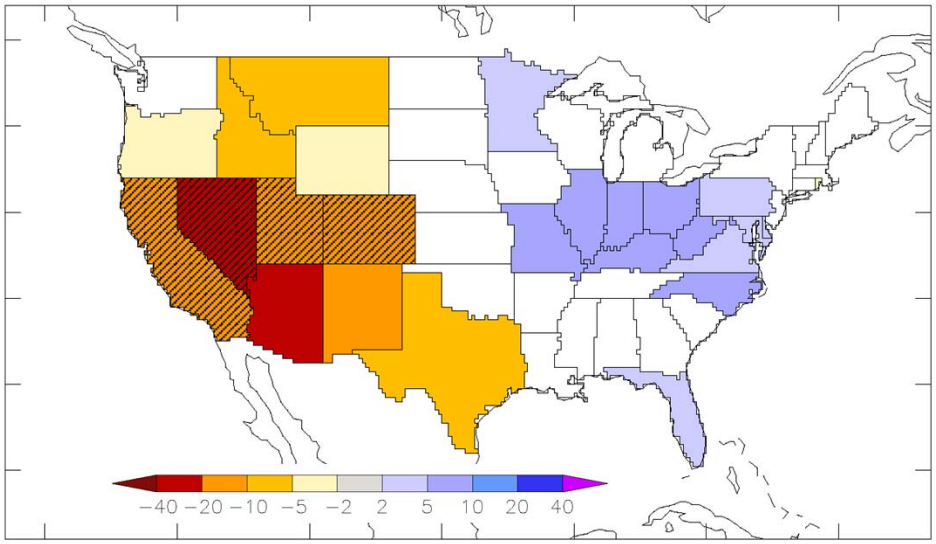

Figure 6.2. Model-projected percentage change in annual runoff for future period, 2041-2060, relative to 1900-1970 baseline (using the A1B scenario projections). Any color indicates that greater than 66 percent of models agree on sign of change; diagonal hatching indicates greater than 90 percent agreement. (Online supplement to Milly, et al., 2005.)

6.3.4 Soil Moisture

The amount of water in the soil that is available for uptake by vegetation is generally referred to as soil moisture. Hayhoe et al. (2007) suggest a general increase in dry conditions (with respect to soil moisture) though with large spatial variability in the future. This drying is mainly caused by increased evapotranspiration due to higher temperatures and decreased summer/early fall precipitation. Their study also suggests that spring soil moisture is likely to be much higher (particularly for high emission scenarios) due to higher winter precipitation and earlier snowmelt (Hayhoe et al., 2007). A trend towards decreasing soil moisture in North America has also been shown in a recent study by Sheffield and Wood (2008).

Using a parsimonious soil water balance model developed by Porporato et al. (2004), which represents a stochastic model of the soil moisture dynamics, we can assess relative changes in the probability distributions of soil moisture under different climatic conditions (Fig. 6.3). The model is described in detail in Appendix 2. For typical soil and vegetation characteristics we see that the soil moisture probability density functions (PDF) shift towards drier conditions (to the left) for both the A2 and B1 emission scenarios. A soil moisture value of 1 would mean that the soil is always wet, while a value of 0 indicates that the soil is always dry. The actual modeled values are less reliable than the relative change between time periods and scenarios due to the simplicity of the model used. Differences between the A2 and B1 emissions scenarios are rather small, which is similar to results reported in Boesch (2008) for the state of Maryland. A summer decrease in soil moisture should therefore be considered likely. How far such drying will result in plant stress will depend, among other things, on the rooting depth of the vegetation. Figure 6.4 shows the variability of the PDF with variation in rooting depth. This result suggests that vegetation with shallow roots will feel more stressed.

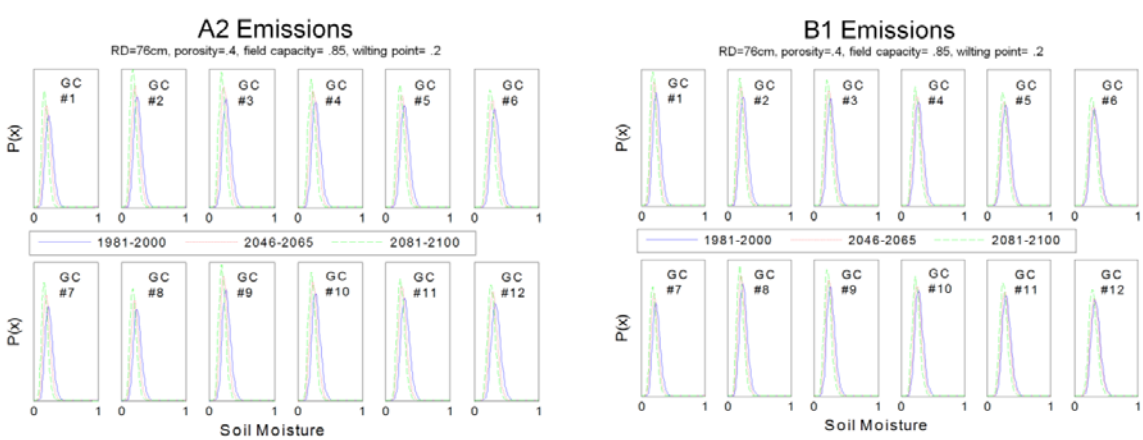

Figure 6.3. Soil moisture probability density functions for different soil and vegetation characteristics (RD: rooting depth) and for different climatic conditions (mainly average temperature, rainfall depth and frequency) during the growing season for control, future 1

and future 2. GC refers to the different grid cells for which precipitation and temperature have been estimated.

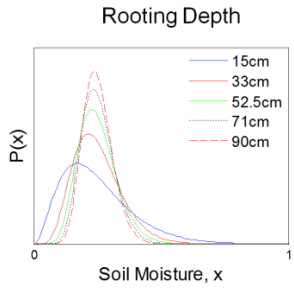

Figure 6.4. Variability of soil moisture probability density functions with variability in rooting depth.

6.3.5 Groundwater

Precipitation that infiltrates into the ground, and is not taken up by plants, percolates to deeper soil layers and eventually recharges the groundwater. Pennsylvania groundwater characterization is difficult due to the complex geology in the state. Most groundwater, however, is stored in so-called consolidated aquifers. These are aquifers that consist of limestone, sandstone, granite or other rock that hold water in interconnected fractures and pore spaces. How much water is contained in an aquifer and how fast it moves depends on the aquifer's specific characteristics. As mentioned earlier, most of the groundwater recharge occurs in the spring, while groundwater levels decline during the remaining year. More than a third of the population of Pennsylvania use groundwater from wells and springs as drinking water or for domestic use in general. While higher winter precipitation and higher temperatures could lead to increased recharge, detailed studies of climate change impacts are not available yet. One also has to consider that *any increases in precipitation are unlikely to replace groundwater substantially enough to compensate excessive withdrawals of some aquifers* (Boesch, 2008), which means that future population (and thus demand) scenarios are as (or even more) important for this resource as (than) climate change projections. One also has to keep in mind that other environmental changes, for example increasing urbanization, have significant impacts on groundwater recharge that can exceed the impacts of climate change. *Every acre of land that is covered with an impervious surface generates 27,000 gallons of surface runoff instead of groundwater recharge during a one-inch rainstorm* (Swistock, 2007).

6.3.6 Stream Temperature

The water temperature of streams has important direct and indirect implications for aquatic organisms. Each organism generally has a particular temperature range, which generally changes with its life stage, in which it can survive. In addition, temperature affects water properties such as dissolved oxygen content and nutrient concentrations that are important for habitat quality. Stream temperature is strongly correlated with air temperature for many streams unless they receive considerable groundwater influx (Morrill et al., 2005). The relationship between air and stream temperature can thus be

used to obtain a first order assessment of the likely implications of air temperature increase for streams. Figure 6.5 shows linear regression relationships between air and stream temperature derived for six streams of different size in Pennsylvania. One can clearly see that stream temperature can be estimated quite well for all but one of the streams (Big Spring Creek). The water temperature in this spring-fed stream is rather independent of air temperature. In most streams, an increase of 1 degree C in air temperature will lead to about 0.7 degrees C to 0.9 degrees C increase in water temperature. This result is typical for many streams in diverse geographical settings and should be robust even if air-stream temperature relationships can sometimes be slightly non-linear (Morrill et al., 2005). The impact of assuming linearity should be considered minor considering other uncertainties in the data.

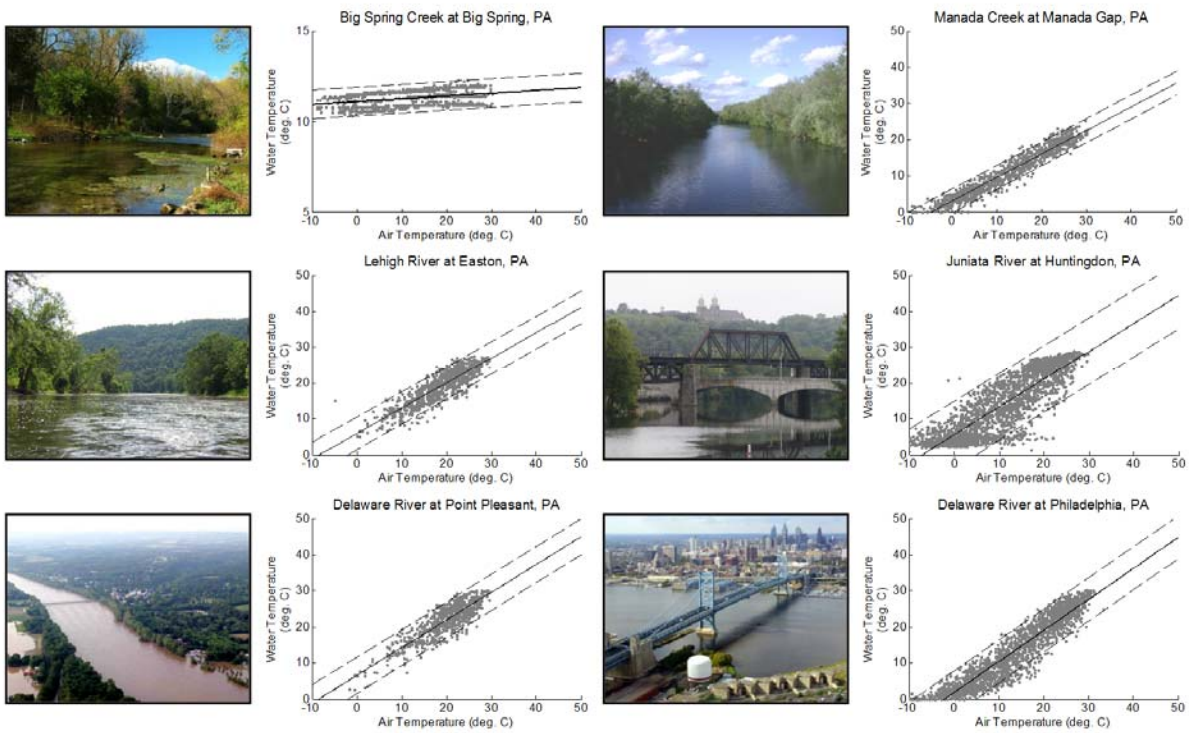

Figure 6.5. Pictures of analyzed rivers and linear regression plots of daily air temperatures versus water temperatures for all six locations. Most streams will see an increase in water temperature with increasing air temperature, though some spring-fed streams might be relatively insensitive to these changes. The combined effect of higher water temperatures and lower summer streamflow is likely to cause problems for aquatic ecosystems and increased competition for freshwater resources. See Appendix 3 for further details on this analysis.

6.4 Impacts for Pennsylvania Freshwater Services and Disservices

We can define the benefits received by nature (ecosystems) and humans from freshwater resources as services and the negative impacts as disservices (Wagener et al., 2008). This section is based on a mixture of quantitative results and qualitative interpretation of what is currently known or of data that are currently available. One has to keep in mind that

General Circulation Models have particular limitations when it comes to capturing extremes (e.g. in relation to meteorological drivers of floods and droughts) due to their focus on longer term and large scale patterns. At the global scale, a region such as Pennsylvania has to be seen as being a low stress region, i.e. based on ratio of water withdrawals to available water. One also has to keep in mind that potential population increase and urbanization might have impacts on the water cycle that can often exceed the direct impact of climate change, at least in the near future. At the same time, water conservation strategies can significantly reduce water use or maintain constant levels even under growing population as recorded elsewhere, for example in Maryland (Boesch, 2008).

6.4.1 Floods

Flood events are generally the result of extreme precipitation events. They are as such relatively difficult to predict even under conditions of stationarity of the climatic and environmental systems. Historically the frequency of floods with certain magnitudes is typically predicted using statistical hydrology. In this approach historical records are analyzed to identify a probability distribution that describes the historical occurrence of a flood of a given size. Assuming stationarity, these probability distributions can then be used to calculate design floods etc. However, the assumption of stationarity is not suitable for climate change impact assessment and recent papers call for the development of new approaches to replace current techniques (e.g. Milly et al., 2008). Since even past analyzes of flood frequency were uncertain it is likely that estimates under conditions of climate change are even more unreliable. In particular since precipitation extremes are poorly captured in current General Circulation Models due to the large spatial scales of the grid cells over which they average atmospheric conditions, and due to unresolved biases in downscaling methods.

Winter and spring floods will likely be impacted by changes in winter precipitation and by the reduction in snow-cover extent and snow water equivalent. There is a general trend towards higher winter precipitation, which will translate into a tendency for streamflow to be higher in winter and spring. Rain on snow floods can be significant in the Susquehanna River Basin. During such events, large amounts of snow melt quickly during a precipitation event potentially resulting in extreme flood events. The Susquehanna River Basin witnessed such an extreme flood in January 1996. The projected reduction in snow pack might lead to a reduction of flood events of this type. Conversely, peak flooding is likely to increase in urban environments due to an increase in impervious areas and higher rainfall variability. Subsequent flashier runoff regimes and increasing water temperature will likely have negative implications for aquatic ecosystems (Boesch, 2008). A more detailed investigation of potential future flooding in the Susquehanna River Basin is crucial since is represents one of the most flood-prone areas in the whole US, *experiencing a major devastating flood on average every 14 years* (SRBC, 2006).

6.4.2 Droughts

Drought can be defined differently depending on its length and depending on the hydrological variables impacted (Fig. 6.6). A meteorological drought is mainly based on lack of precipitation and generally very short in duration (NWS, 2006). An agricultural drought relates mainly to a deficit in soil moisture with subsequent plant water stress and potential reduction in biomass production – most climate change impact studies for the northeastern US have focused on this kind of drought. Droughts resulting from the longer-term impacts of lack of precipitation and increased evapotranspiration are generally referred to as hydrological droughts. They manifest themselves in reduced streamflow, lower reservoir and lake levels as well as lower groundwater levels (NWS, 2006). As discussed above, increased summer temperatures will likely shift soil moisture distributions to drier regimes, thus increasing plant stress and potentially decreasing plant productivity. The strength of the impact will differ with plant rooting depth and thus moisture availability for individual plants. Pennsylvania will likely see an increased frequency of short-term droughts while the overall annual runoff increases slightly. Lower summer and fall streamflow could provide problems through competing uses, e.g. power plant cooling versus environmental flows, especially in combination with increased water temperatures (see water quality section). The largest drought on record in Pennsylvania occurred during the period from 1962 to 1965 and will likely remain an extreme event despite increases in future summer air temperatures (Hayhoe et al., 2007). This drought was the consequence of an extended period of low precipitation (Namias, 1966).

At the same time as summer flows might be lower, winter precipitation will likely increase (Figure 5.7a) which could result in fuller freshwater reservoirs at the beginning of the summer and thus allow for an opportunity to reduce any impasses through adjusted water management. *Water-supply drought is more heavily affected by periods of low precipitation extending over multiple months, and is most strongly correlated with dry periods persisting through winter and spring when soil moisture, water tables, and reservoir levels would normally experience recharge* (Boesch, 2008).

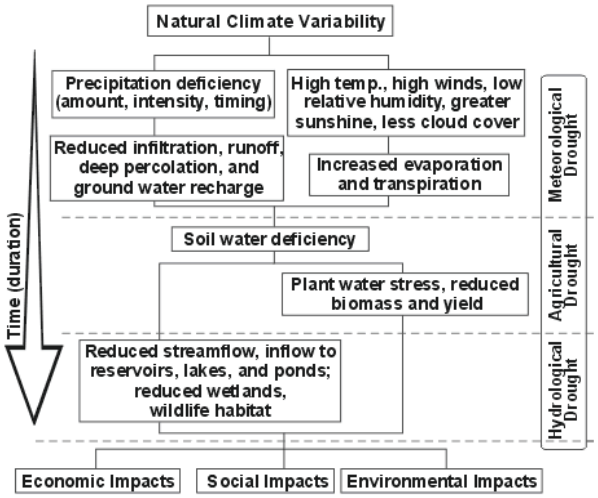

Figure 6.6. Flow chart visualizing the differences between meteorological, agricultural and hydrological droughts. (From National Drought Mitigation Center, http://www.drought.unl.edu/whatis/concept.htm, Accessed February 2009)

6.4.3 Water Quality

Increased variability in streamflow is likely to occur, which means that there will be a tendency for higher winter and spring flows, but lower summer and fall flows. Figure 6.4 suggests that many freshwater streams are well mixed and that their temperature will respond quickly to increasing air temperatures. Lows flows and higher water temperatures are likely to decrease habitat suitability for aquatic biota since it will lead to a decrease in dissolved oxygen content. Increased variability of flow, changes to the timing of peak spring flow and changing water temperature will likely negatively impact aquatic ecosystems. Lower summer stream flows could also lead to the loss of small wetlands, thus further impacting water quality throughout the river network negatively. Degraded streams and flashier runoff would further increase water quality impairments in the Chesapeake and Delaware Bays due to flushing of nutrients and sediments into the estuary (Boesch, 2008).

6.4.4 Salt Water Intrusion in the Delaware Estuary

When one thinks of Pennsylvania, the ocean does not usually come to mind. However, Pennsylvania's connection to the sea, The Delaware Estuary, is one of the state's most valuable economic and ecological resources. The estuary is home to the largest freshwater port in the world, generating $19 billion annually and receiving 70 percent of the oil shipped to the U.S. East Coast. The combined river/estuary system provides drinking water to 15 million people (including many Pennsylvanians), is a source of water for industrial processes, and receives wastes from municipal and industrial wastewater treatment plants. The estuary also supports the largest horseshoe crab population in the world and is one of the world's most important sites for shorebird migration.

Climate change has the potential of altering estuaries through, for example, changes in temperature, winds, streamflow, and sea level, which will affect numerous estuarine characteristics, such as circulation, water quality, and ecology. Salinity is an important defining characteristic of the Delaware estuary, regulating floral and faunal distributions and affecting human use of the estuary. A major objective of the Delaware River Basin Commission (DRBC) is to regulate streamflow through the use of reservoirs so as to keep water supplies safe for human consumption and industrial uses. The DRBC attempts to keep potable supplies at sodium concentrations less than 50 ppm, the NJ drinking water standard. However, the American Heart Association (AHA) recommends sodium levels less than 20 ppm. The EPA chloride standard is 250 ppm, and is also the concentration at which water begins to taste salty. DRBC salinity controls are also in place to protect groundwater, which is fed in part from the estuary. It has been determined that a chloride concentration at Philadelphia less than 180 ppm will keep well waters potable (Hull et al., 1986).

There is strong evidence that past climate-induced changes in Bay salinity have had negative impacts on water supply systems. The drought of 1930 resulted in Delaware River chloride concentrations as high as 500 ppm at Philadelphia, PA and exceeding 1000 ppm at Chester, PA (Mason and Pietsch, 1940). In 1951, Chester changed its water source from the Delaware River to the Susquehanna River Basin because of increases in salinity; it has been suggested that these were caused by sea-level rise (Parker, 1964) and low streamflow (Hull et al., 1986). In 1964, drought conditions resulted in chloride concentrations of 250 ppm in Philadelphia, an emergency declaration by the DRBC, and economic damages (Hull et al., 1986).

Sodium and chloride levels of the Delaware River at Philadelphia have steadily increased from the early 20th century to the present day (Philadelphia Water Department, 2007), likely from changes in land use in the watershed, increased wastewater discharges, but also possibly from the increase in sea level of approximately 0.28 m (Zervas, 2001) that occurred during this time. Current (2003-2005) mean levels of chloride and sodium are 23 and 15 ppm, respectively, and extrapolation of recent trends suggests that the mean sodium level will exceed the AHA criterion in 100 years.

However, sea level is very likely to keep increasing throughout the 21st century, which will increase trends of sodium and chloride in the Delaware River and Estuary. Rahmstorf (2007) estimated that global mean sea level will rise by 0.5 to 1.4 m by the end of this century, where the range expresses uncertainty in the particular CO_2 emissions scenario and in the response of the climate to CO_2. For the Delaware Estuary, these projections need to be increased to account for local impacts on the relative position of the land and the sea, including land subsidence due to geological processes. Global mean sea level rose at a rate of approximately 1.8 mm yr^{-1} during the second half of the 20th Century (Church et al., 2004). At the two locations in the Delaware Bay sampled during this time, Philadelphia, Pa. and Lewes, Del., sea-level rise was 2.74 ± 0.35 and 3.04 ± 0.29 mm yr^{-1}, indicating a local component of sea-level rise of about 1 mm yr^{-1}. Thus sea-level projections for the Delaware estuary should be increased above the global average to 0.6 to 1.5 m by the end of this century.

Three modeling studies have been conducted to assess the potential impact of sea-level rise on the Delaware Estuary. Hull and Tortoriello [1979] used a 1-D model to investigate the impact of a 0.13 m rise in sea level. They ran the model for conditions experienced during the 1964-1965 drought, and found that the sea-level increase resulted in a 5-140 ppm (10-21 percent) increase in chloride concentration between river miles 80 and 115. At Philadelphia's Torresdale water intake (River Mile 110), the chloride increase was 4 ppm. The U.S. Army Corps of Engineers (1997) conducted simulations using a 3-D model and found a 20-ppm chloride increase at River Mile 98 for a sea-level increase of 0.3 m. Kim and Johnson (2007) used an updated version of this model to evaluate the impact of a 0.16-m increase in sea level, finding a chloride increase of 7 ppm (10 percent) at the Ben Franklin Bridge. These studies collectively suggest that, in the vicinity of Philadelphia, chloride increases roughly 3-6 ppm for every 0.1 m of sea level increase. Thus, sea level projections of 0.6 to 1.5 m by the end of this century imply

chloride increases of 18 to 90 ppm—anywhere from a doubling to a quadrupling of current chloride levels.

In addition to sea-level rise, salinity of the upper Delaware Estuary is likely to change as a result of climate-induced changes in streamflow. Unfortunately, the projected change in annual streamflow is rather uncertain. However, streamflow variability is expected to increase, so even though quantitative projections are not possible at this time, it seems likely that drought-induced saltwater intrusion events will increase throughout the 21st century.

6.5 Adaptation Strategies

Any climate change policy must consider some degree of adaptation since – even under the most optimistic emission scenario – we are committed to a certain degree of climate change, the impacts of which can already be felt in many regions. Following the IPCC, adaptation can be defined as *initiatives and measures to reduce the vulnerability of natural and human systems against actual and expected climate change effects*. A wide range of options for adaptation exist and some of the more common ones are listed in Table 6.2. Adaptation strategies for water management under potential climate change have to be developed while considering scenarios for future regional population and economic development. As discussed at multiple places within this section, population growth, urbanization and other land cover change, and pollution of water bodies could be equal or even more important stressors than climate change at least in the near future. A holistic approach to developing adaptation strategies will be required, while the existing uncertainty in current projections of climate change impacts suggests that "no regret" strategies might be the best option for now. Strategies are classified as "no regret" if they lead to societal benefits regardless of the degree of climate change. Examples of such strategies include water conservation and better monitoring of hydrological and other environmental variables.

Water-use sector	Supply-side measure	Demand side-measure
Municipal water supply	Increase reservoir capacity	Incentives to use less (e.g. through pricing or rebates)
	Extract more water from rivers and groundwater	Legally enforced water use standards (e.g. for appliances)
	Alter system operating rules	Increase use of grey water
	Inter-basin water transfer	Reduce leakage
	Capture more rain water	Increase use of recycled water
	Desalination	Development of non-water-based sanitation systems
	Seasonal forecasting	
Irrigation	Increase irrigation source capacity	Increase irrigation-use efficiency
		Increase use of drought tolerant plants

		Alter cropping patterns
Industrial and power station cooling	Increase source capacity	Increase water-use efficiency and water recycling
	Use of low-grade water	
Hydropower generation	Increase reservoir capacity	Increase efficiency of turbines, encourage energy efficiency
Navigation	Build weirs and locks	Alter ship size and frequency
Pollution control	Enhance treatment works	Reduce volume of effluents to treat (e.g. by charging for discharges)
		Watershed management to reduce polluting runoff
Flood management	Increase flood protection (levees, reservoirs)	Improve flood warning and dissemination
	Watershed source control to reduce peak discharges	Curb floodplain development

Table 6.2. List of examples for supply- and demand-side adaptation strategies. (Source: Cooley, 2009)

6.6 Challenges and Opportunities

There are two main barriers to understanding the potential implications of climate change on Pennsylvania's water resources: [1] insufficient monitoring of hydrological variables, and [2] lack of state-wide hydrologic modeling studies to interpret past observations and future projections of climate. Both aspects will be discussed in more detail below.
Any scientifically valid assessment of current and past conditions of the water cycle in Pennsylvania has to be based on observations of the main hydrological variables (streamflow, soil moisture, snow water equivalent, groundwater, water quality) and their meteorological drivers. The river networks of many drainage basins in the eastern US (including Pennsylvania) are characterized by a large fraction of small (low order) streams. It is increasingly recognized that these headwater streams often control water quantity and quality through much of the river network. However, continuous streamflow gauging stations are heavily biased towards larger streams, meaning that for much of the basin we only have observations of the large-scale integrated streamflow response. This issue limits our ability to provide reliable benchmarks of past and current hydrological conditions in most headwater streams. This problem is exacerbated by a lack of soil moisture and snow measurements as well as a lack of coordinated assessments of large-scale groundwater dynamics. The monitoring of hydrological variables has to go hand-in-hand with observations of changes to land cover and population size. The former is important since changes to land cover, in particular the extension of impervious areas, is likely to have significant impacts on water flow paths. Population size and people's water use behavior is likely to impact water demand, which is one important stress on current and future freshwater resources and thus has to be monitored.

The lack of appropriate spatially-distributed data means that hydrological models have to be used to extrapolate hydrological characteristics in space and time. Scientific studies of past and future hydrologic conditions across the state have so far been limited to snapshots often using the output of only a few GCMs, aggregating over large areas, or not providing estimates of confidence in the streamflow (or other) simulations provided. Continuous advancement in watershed-scale hydrologic models and increasing availability of high-performance computing continuously reduces these limitations though. Another barrier related to the use of hydrological models, currently of great interest to the research community, lies in the problem that the hydrological system itself is not stationary. For example, changes in climatic conditions such as temperature and frequency of rainfall impact vegetation and soil characteristics, which in turn alter hydrological flow paths. These changes are often gradual and the evolution of the hydrological system has thus far been ignored, thus assuming that non-stationarity only occurs in the boundary conditions, i.e. the climate. New approaches to include the evolution of the hydrological system itself in our models have to be developed to address this issue.

The redistribution of freshwater resources due to a change in winter precipitation and due to a general warming trend in Pennsylvania might provide opportunities for improved water management strategies (see Table 6.2). Increased precipitation in liquid form during winter and spring months might enable improved groundwater recharge (naturally or artificial) and increased storage of water in reservoirs or the sub-surface to support summer water demands. These water management strategies will in particular have to consider competing summer demands under climate, population and economic change scenarios while considering environmental constraints. Opportunities for adaptation strategies are discussed in section 6.5.

6.7 Information Needs

Information needs are strongly connected to the barriers discussed in the previous section: improved monitoring and more detailed hydrologic modeling studies. Improved monitoring is necessary to enable better quantification of magnitude and trends in major hydrological variables. In particular the lack of continuous snow and soil moisture measurements limits the direct assessment of climate change impacts and the evaluation of hydrological models. In addition to hydrological variables it is crucial to understand water demand patterns and trends across the state, both agricultural and municipal industrial. The latter is needed since human imposed stresses on Pennsylvania's freshwater are likely to be very important to understand overall water cycle dynamics. The value of some historical data to support the assessment of potential future conditions using for example statistical analyses is likely to decrease, though understanding trends in the data is likely to remain very important. Statistical approaches – often the basis of current water resources engineering – will have to be replaced with new model-based strategies that allow for the inclusion of the non-stationarity of the system. Regional models have to be implemented and tested to interpret trends in historical hydrological data and to extrapolate hydrologic conditions in space and time. Such modeling studies

need to be performed especially to provide better information regarding potential future flooding (rain on snow) and recharge to groundwater. Current studies are generally too coarse in their spatial and temporal resolution. Information about the uncertainty in climate change projections needs to be included in these modeling studies and these uncertainties have to be propagated into ecological and water resources endpoints (e.g. flood frequencies or water temperature ranges).

6.8 Conclusions

Management of Pennsylvania freshwater resources requires a balance between the competing societal and environmental needs placed on the basin's freshwater resources. Humans and ecosystems are embedded in the watershed systems, which exhibit a wide range of characteristics depending on their location and their degree of human activity. The watersheds internal heterogeneity means that we are dealing with complex and uncertain systems. An important task is to support the development of sustainable integrated resource management strategies through environmental models which enable us to understand these complex systems and to predict their response to future environmental change. This predictive capability is necessary to achieve water security for people (both current and future generations) and the environment in an increasingly non-stationary world (Falkenmark, 2001; Milly et al., 2002; 2005), for which water security can be defined as protection from both water excess and water scarcity (Gleick, 2002). Models of water-driven environmental systems play an important role in understanding human and climate impacts. There is a growing recognition within the scientific community (Reed et al., 2006; National Research Council, 2008; Wagener, 2008) that the management of large-scale water resources under uncertainty requires community level advances for developing and evaluating predictive models as well as new frameworks for using these models to enhance monitoring systems. As noted by Dooge (1986), our ability to understand, predict and manage hydrologic systems is dependent on our ability to characterize both the natural and human systems that shape their evolution.

This section discussed the current understanding regarding the implications of climate change on Pennsylvania water resources. Throughout this discussion it is important to remember that the IPCC scenarios present potential futures of our world, none of which has to actually occur, though all are possible. The process of assessing the implications of these scenarios, through General Circulation Models and local hydrological models of varying complexity, contains uncertainties that have thus far not been quantified. The confidence with which we can make statements about potential impacts therefore differs for the various elements of the water cycle.

Main conclusions regarding the future of Pennsylvania water resources are largely based on changes to atmospheric moisture and energy availability. Precipitation is projected to increase in winter and stay relatively stable in the summer, with the potential for a small increase. Heavy precipitation events are also projected to increase. At the same time temperature is projected to increase throughout the year. One consequence of this change would be a significant decrease in snow cover extent and duration throughout

Pennsylvania. More precipitation would fall as rain, rather than as snow. Increasing temperature is likely to lead to increasing evapotranspiration. Since most of the actual evapotranspiration in Pennsylvania occurs in the summer (and little in the winter), and summer precipitation and evapotranspiration are already about equal, it is likely that we will see an increase in soil-moisture-related droughts throughout late spring to early fall. The frequency of short and medium length soil moisture droughts is thus projected to go up. On the other hand, groundwater recharge could increase due to fewer days with frozen ground and more precipitation during the winter time when evaporation is low and plants are not active. Summer floods and general flow variability are projected to increase. A reduced snowpack might cause a reduction in rain on snow events, a process which historically caused major flooding events in Pennsylvania, though this conclusion remains speculative before more detailed studies have been executed.

Overall, Pennsylvania is likely to see a small increase in runoff in the order of 5 to 10 percent. However, this increase will basically all be during the winter months while summer flows might actually be reduced. The interaction with changes to groundwater recharge and the potential for more baseflow is less clear at the moment. Stream temperature, an important water quality characteristic for aquatic ecosystems, is likely to increase thus potentially causing problems for certain fish and other species which require cold water for at least part of their life cycle. This increase in water temperature in combination with flashier runoff due to more extreme precipitation and due to increased urbanization would negatively impact Pennsylvania water quality and potentially impair estuaries into which the river network drains. At the same time, higher sea levels would increase salt water intrusion in coastal waters. Table 6.3 summarizes the main conclusions of this section and also provides a statement of confidence associated with each property.

Property	21st Century Projection
Precipitation	Increase in winter precipitation. Small to no increase in summer precipitation. Potential increase in heavy precipitation events [High confidence for winter, lower for summer]
Snow pack	Substantial decrease in snow cover extend and duration [High confidence]
Runoff	Overall increase, but mainly due to higher winter runoff. Decrease in summer runoff due to higher evapotranspiration [moderate confidence]
Soil moisture	Decrease in summer and fall soil moisture. Increased frequency of short and medium term soil moisture droughts [Moderate confidence]
Evapotranspiration	Increase in temperature throughout the year. Increase in actual evapotranspiration during spring, summer and fall [High confidence]
Groundwater	Potential increase in recharge due to reduced frozen soil and higher winter precipitation when plants are not active and evapotranspiration is low [Moderate confidence]
Stream temperature	Increase in stream temperature for most streams likely. Some

	spring fed headwater streams less affected [High confidence]
Floods	Potential decrease of rain on snow events, but more summer floods and higher flow variability [Moderate confidence]
Droughts	Increase in soil moisture drought frequency [Moderate confidence]
Water quality	Flashier runoff, urbanization and increasing water temperatures might negatively impact water quality [Moderate confidence]
Salt water intrusion	Increase in salt water intrusion (in estuaries) due to rising sea levels [Moderate confidence]

Table 6.3. Summary of general projections for Pennsylvania water resources.

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7.0 Forests and Wildlife

Pennsylvania is named for its forests. Forests once covered more than 90 percent of the land area of the state, and even today they are the dominant land use, covering some 58 percent of the state's land (McWilliams et al. 2007). The decline in overall forest area occurred in the 19th and early 20th centuries when the state's forests were cleared for agriculture and almost completely logged over; the area of forest land in the state has been stable or increasing for the past century. The northern part of the state is heavily forested and dominated by northern hardwoods – maple, beech and birch forests. Land cover in the southern part of the state is more mixed, with forestland interspersed with agricultural and urban land. Mixed oak forests dominate in southern Pennsylvania.

Forests are important to the economy of the state. The state's forest products industry annually generates revenues of more than $5.5 billion and employs about 90,000 people, more than 10 percent of the people employed in manufacturing in the state (PFPA 2004). The forest products industry is a critical part of the local economies of many rural counties in the state. Forests are also important for recreation: Pennsylvanians enjoy their forests while hiking, camping, hunting, fishing, canoeing, horseback riding, bird-watching, and simply driving through them. Furthermore, the state's forests provide a number of important ecosystem services, including refugia for a host of wildlife species, provision of clean water, and carbon sequestration and storage.

These valuable resources are threatened by climate change. A growing body of evidence indicates that global climate change is already negatively affecting ecosystems in general (Parmesan and Yohe 2003, Parmesan and Galbraith 2004) and forest ecosystems in particular. For example, van Mantgem et al. (2009) document higher rates of mortality in northwestern forests, which they attribute to climate change. Soja et al. (2006) document species migrations, increased mortality of some species, and increased insect and disease outbreaks in the boreal forests of Siberia, Canada and Alaska, changes consistent with the predictions of global circulation models (GCMs). Also, increased fire frequency and severity (Westerling et al. 2006) and dramatically increased mortality rates from bark beetles (Breshears et al. 2005, Logan and Powell In press) and drought (Breshears et al. 2009) in the forests of the western US have been linked to climate change. Changes in eastern US forests are less well documented, although Woodall et al. (2009) identify much higher seedling densities for northeastern tree species in the northern parts of their ranges than in the southern parts of their ranges, suggesting that tree migration in response to climate change is occurring through better regeneration success at the northern end of the species' ranges. Furthermore, GCMs, coupled with species suitability models (e.g., Iverson et al. 2008a, 2008b), indicate that the suitable habitats for eastern North American tree species will shift northward in the coming decades.

These changes will occur within a context of forest ecosystems that have been already subjected to major anthropogenic disturbances within the past two centuries and that continue to suffer from significant additional stressors today. Pennsylvania's forests have experienced several waves of exploitation, beginning in the early 1800s with clearing of large areas for agriculture, charcoal harvesting to supply the state's early pig iron

industry, and selective harvesting of tall white pines for ships' masts. These initial waves of harvesting were followed by periods of chemical wood harvesting and harvesting of hemlocks for compounds in their bark that were used to tan leather. Finally, the development of narrow gauge railroads following the Civil War provided greater access for loggers, and between 1880 and the 1930 nearly all the state's original forests were harvested (Whitney 1990). Additionally, during this period millions of acres that had once been forested burned, as the large quantities of slash left in the cutover areas were ignited by sparks and hot cinders from the coal-fired locomotives passing through to the next harvest area (Brose et al. 2001).

The harvesting and fires of the late 1800s and early 1900s dramatically changed the species composition of Pennsylvania's forests, greatly reducing the extent of once-common species such as white pine, hemlock and beech and increasing the dominance of oaks (Whitney 1990, Brose et al. 2001). The American chestnut probably would also have benefited from the radically altered disturbance regime of the period, but the chestnut blight, an exotic (non-native) disease from Asia, swept through the state in the early part of the 20th century, virtually eliminating this once-dominant species from the state's forests (Liebhold et al. 1995). Other exotic diseases, including Dutch elm disease and beech bark disease, have had similar, if somewhat less devastating impacts on other important tree species. In addition, exotic insects, such as the hemlock wooly adelgid, the gypsy moth, and the emerald ash borer, are wreaking havoc with key tree species today (Gottschalk 2007). Furthermore, the state's forests are being invaded by non-native plants, including trees such as ailanthus and Norway maple, shrubs such as bush honeysuckle, multiflora rose, Japanese knotweed, Japanese barberry and privet, and herbaceous plants such as Japanese stiltgrass and mile-a-minute weed (Webster et al. 2006). Finally, atmospheric deposition has substantially altered the soil chemistry of at least some of the state's forest soils, and some species, particularly sugar maple, have been shown to be very sensitive to these changes (Horsley et al. 2000, 2008, Driscoll et al. 2001, Fenn et al. 2006).

While less than one percent of the state's original forests is preserved as old-growth and in spite of the multiple anthropogenic assaults, the state's forests are once again extensive and relatively mature. Nevertheless, the forests face other significant stressors, including forest loss and fragmentation due to development (Riitters et al. 2002, Lister et al. 2005), parcelization into increasingly difficult-to-manage small ownership blocks(Alig 2006), unsustainable harvesting practices, and regeneration problems (McWilliams et al. 2005, 2007). So, climate change can be viewed as just one more stressor within this increasingly challenging forest management context. Adapting to a changed climate will be complicated by many of these problems, and a changing climate will likely exacerbate others.

This chapter attempts to summarize what is, in fact, a vast literature. A sincere attempt has been made to include the most important articles, reports, books, and book chapters relevant to the question of how Pennsylvania's forests may be affected by climate change during the 21st century, but it is likely that important contributions have been missed. The chapter begins with a review of projected biological changes that have been

projected to take place in Pennsylvania's forests under the conditions projected by various GCMs. These include generally northward shifts in the potential suitable habitat for tree species that could result in many common species becoming less common and improved habitat for species currently found primarily to the south of the state. Projected biological impacts also include increased disturbance rates and increased potential productivity rates. The next section describes some of the more important changes that have been projected for the state's terrestrial ecosystems. As with tree species, the ranges of most species of plants and animals are projected to shift northward. Species that have narrow ranges and limited ability to migrate would be at the greatest risk of extinction. The following section discusses some key challenges that may occur for the state's forest products industry in the coming decades as a result of climate change. A major challenge for the industry will be to identify which species and genotypes of trees will thrive in the future climate of the state and then regenerating today's forests with those trees. The chapter concludes with discussions of ways that forests can contribute to mitigating the drivers of climate change, primarily emissions of carbon dioxide to the atmosphere, and recommendations for adapting to these changes, to the extent that they do occur.

7.1 Projected Biological Changes

A warming climate is likely to have numerous impacts on forest ecosystems and the humans who work and play in them. First, climate change is projected to shift the ranges of tree species generally northward. Obviously, individual trees cannot move to new habitats, so trees in habitats that become increasingly unsuitable for them will be stressed. As this occurs, mortality rates would likely increase and regeneration success would likely decline, resulting in declining populations of those species in the state. Increased stress due to climate change will likely make some species more susceptible to a host of other stressors, including atmospheric deposition and both native and non-native insects and diseases. Tree mortality could rise due to these secondary impacts, and it may be difficult to attribute the changes directly to a changing climate. Tree mortality could also increase if climate change increases the frequency of droughts and severe storms. On the other hand, as the habitat becomes less suitable for one suite of species, the habitat will become more suitable for others. Some of those species are already present in Pennsylvania, and their numbers will likely increase as they experience greater regeneration success and survival. Some species that might find suitable growing conditions in Pennsylvania as the climate changes are not presently here. Since trees have limited ability to colonize new areas far distant from where they are currently found, migration of these species could be slow without human intervention. As species respond in individual ways to climate change, the common associations of species we now see, called forest types, may also change.

Climate change may also change the productivity of the forest ecosystems of the state. To the extent that trees become stressed because they are no longer well suited to the climate where they are, their growth rates will likely decline. On the other hand, warmer temperatures, longer growing seasons, and the "CO_2 fertilization effect" may lead to faster growth rates for some species. This section reviews the state of the current

research relevant to how the forests of Pennsylvania are likely to respond to climate change.

7.1.1 Species Shifts

The ranges of tree species in eastern North America have generally shifted northward as the climate has warmed over the past 11,000+ years since the last ice age (Davis 1969, Delcourt and Delcourt 1981, Webb et al. 1987, Schmidtling 2007). However, the ranges of different species have shifted differentially, resulting in changing forest community compositions over time. Similar species-specific reponses to climate change are likely to occur over the next century. For Pennsylvania, this means that some species will decline in abundance while others will increase (McKenney-Easterling et al. 2000). Some species will likely disappear from Pennsylvania's forests entirely. While it is likely that the climate of the state will become suitable for some species not currently found in the state, it is less clear how rapidly – or even whether – those species will migrate to the state without active human intervention (Higgins and Harte 2006). This is because of the relatively rapid nature of the projected climate shifts and limits on the rate at which trees can migrate over a landscape. Species migration will also be hindered by the fragmented nature of modern landscapes.

Researchers at the USDA Forest Service's Northern Research Station have developed models to project shifts in the potential suitable habitat for various tree species under different climate change scenarios (Iverson and Prassad 1998, 2001, 2002, 2003, Iverson et al. 1999a, 1999b, 2004a, 2004b, 2005, 2007, 2008a, 2008b, Prassad et al. 2006). Their models use climate, elevation, soils and land use information to predict the current distribution of species across the eastern United States (US), based on the tens of thousands of plots in the USDA Forest Service Forest Inventory and Analysis (FIA) database. Projections of changes in the climate variables from general circulation models (GCMs) are then used to project changes in the potential suitable habitat for 134 eastern US species (Iverson et al. 2008a, 2008b). Maps of Pennsylvania showing the modeled suitable habitat for 36 species under current climatic conditions and under projected climatic conditions 100 years from now under four climate change scenarios are shown in Appendix 6.[1] It is important to keep in mind that the maps do not predict where these species will actually be found; rather they show where the most suitable habitat is projected to exist for each species under different climate scenarios. How and whether species will be able to migrate to regions where they are not currently found is an open question. It is also important to keep in mind that while the projections are a long time off by human time-scales, most tree species live for at least 100 years, so trees that are established now could experience these changed conditions within their lifetimes.

Table 7.1 summarizes the information from the species maps in Appendix 6 by showing the current modeled area-weighted importance values (not their actual values) for the 36 species and the projected changes in these importance values for each species 100 years from now under four climate change scenarios. Two of the scenarios, the High scenarios,

[1] The maps in Appendix 6 were generously provided by Louis Iverson, USDA Forest Service Northeastern Research Station.

Table 7.1. Modeled current and projected changes in area-weighted importance values for selected species in Pennsylvania (Source: Iverson et al. (2008c)).

Scientific Name	Common Name	ClimIndx	ModRely	Current	HadHiDif	PCMLoDif	GCM3AvgHiDif	GCM3AvgLoDif
Betula papyrifera	paper birch	Medium	High	0.08	-0.08	-0.08	-0.08	-0.08
Populus tremuloides	quaking aspen	High	High	0.94	-0.94	-0.80	-0.94	-0.93
Populus grandidentata	bigtooth aspen	High	High	1.17	-1.17	-0.46	-1.17	-0.82
Betula alleghaniensis	yellow birch	High	High	0.90	-0.81	-0.48	-0.80	-0.68
Fagus grandifolia	American beech	Low	High	5.32	-4.19	-2.54	-3.97	-2.97
Prunus serotina	black cherry	Medium	High	9.97	-8.08	-2.95	-9.09	-5.34
Acer pensylvanicum	striped maple	Medium	High	1.20	-0.99	-0.43	-0.93	-0.64
Tsuga Canadensis	eastern hemlock	High	High	2.82	-1.87	-0.93	-1.87	-1.37
Acer rubrum	red maple	Medium	High	14.69	-10.73	-2.00	-10.24	-4.97
Acer saccharum	sugar maple	Low	High	6.63	-5.42	-1.10	-4.10	-1.40
Pinus strobus	eastern white pine	Medium	High	1.98	-1.41	-0.28	-1.34	-0.43
Betula lenta	sweet birch	Medium	High	3.79	-2.43	-0.45	-2.39	-1.32
Fraxinus Americana	white ash	Medium	High	6.17	-3.94	-1.10	-3.67	-1.95
Tilia Americana	American basswood	Low	Medium	0.79	-0.43	-0.06	-0.44	-0.17
Quercus rubra	northern red oak	Medium	High	5.02	-1.60	-0.56	-1.20	-1.02
Quercus prinus	chestnut oak	Medium	High	4.81	-2.12	0.58	-1.99	-0.24
Liriodendron tulipifera	yellow-poplar	Medium	High	2.21	-1.06	0.99	-0.92	0.30
Sassafras albidum	sassafras	High	High	2.46	-0.48	1.07	-0.65	0.91
Carya glabra	pignut hickory	Medium	High	1.37	0.31	0.79	0.44	0.95
Nyssa sylvatica	blackgum	Medium	High	1.77	1.04	0.98	0.99	0.97
Juglans nigra	black walnut	Medium	Medium	0.72	0.01	0.55	0.36	0.70
Quercus alba	white oak	Medium	High	3.57	1.99	1.42	2.94	2.47
Ulmus Americana	American elm	High	Medium	1.36	1.55	-0.06	1.65	0.49
Cornus florida	flowering dogwood	Low	High	1.95	1.03	1.65	1.57	2.24
Carya tomentosa	mockernut hickory	Medium	High	1.17	1.78	0.76	1.64	1.10
Quercus velutina	black oak	Low	High	2.17	3.82	1.16	4.72	2.51
Acer saccharinum	silver maple	Medium	Medium	0.28	1.05	-0.05	0.96	0.29
Juniperus virginiana	eastern redcedar	High	Medium	0.40	3.88	1.31	3.72	2.49
Pinus taeda	loblolly pine	Medium	High	0.01	4.08	0.12	1.78	0.28
Pinus echinata	shortleaf pine	Medium	High	0.01	6.83	0.31	5.18	1.16
Diospyros virginiana	common persimmon	Medium	Medium	0.01	2.91	0.44	2.90	1.09
Morus rubra	red mulberry	Medium	Low	0.00	2.64	0.02	1.96	0.30
Carya texana	black hickory	Medium	High	0.00	4.12	0.26	3.84	1.08
Quercus marilandica	blackjack oak	Medium	Medium	0.00	4.51	0.28	3.83	0.97
Ulmus alata	winged elm	High	High	0.00	6.47	0.38	5.07	1.12
Quercus stellata	post oak	High	High	0.01	14.11	1.37	12.05	3.80

assume that current emissions of CO_2 will continue, while the Low scenarios assume that CO_2 emissions will be significantly reduced. The scenarios are based on the output from three different GCMs: the HadleyCM3 model, the Geophysical Fluid Dynamics Laboratory (GFDL) model, and the Parallel Climate Model (PCM). Two scenarios in the table are based on the averaged output from these models, resulting in an average high-emissions scenario, GCM3AvgHi, and an average low-emissions scenario, GCM3AvgLo. The HadHi scenario is based on the HadleyCM3 model projections under the high-emissions scenario. This model was chosen because it is the most sensitive to projected changes in the concentrations of greenhouse gasses in the atmosphere, so it is used to represent the most extreme warming case. Similarly, the PCMLo scenario uses the least sensitive model and the low-emissions scenario to represent the case with the least warming. The table also shows a model reliability rating index (ModRely), which is a measure of the consistency of the model's predictions for that species based on a procedure that involves refitting the model multiple times with random subsets of the data used to develop the model. The climate index value (ClimIndx) reflects the degree to which climatic variables were found to be the best predictors of where a species is currently found, as opposed to non-climate factors such as elevation, soils, and land use.

The species in the table have been sorted into six broad categories, ranging from those that are likely to be extirpated from the state under the high scenario to species that are currently rare or not found in the state that are projected to find good habitat under the high scenario. The species in the first category are paper birch, quaking aspen, bigtooth aspen, and yellow birch. All these species are currently more common in the northern part of the state or at higher elevations. Paper birch has the smallest amount of modeled suitable habitat under current conditions, and suitable habitat for this species is projected to disappear from the state even under the coolest scenario (PCMLo). Quaking aspen currently has more modeled suitable habitat than paper birch, yet it, too, is largely projected to be extirpated from the state, except under the coolest scenario. Bigtooth aspen is currently modeled to have suitable habitat in most of the state, and its habitat is projected to become limited to the more northern and higher parts of the state under the low-emissions scenarios. The suitable habitat for yellow birch is currently limited primarily to the northern and higher parts of the state. As the climate is projected to warm, its suitable habitat is projected to shrink, but even under the warmest scenarios it is projected to maintain a toehold in the state in the Poconos region.

The importance values of the species in the next category – American beech, black cherry, striped maple and eastern hemlock – are projected to decline substantially (30-56 percent) under the cooler scenarios and dramatically (66-91 percent) under the warmer scenarios. This group includes three of the six most common species in Pennsylvania. American beech is the fourth most common species in the state (McWilliams et al 2007). The most suitable habitat for American beech is currently in the northern part of the state, but suitable habitat is modeled to exist throughout the state under current conditions. Under the cooler scenarios, beech habitat remains distributed throughout the state, but with lower importance values. Under the warmer scenarios, the species' habitat retreats to the more northern and higher parts of the state. This species is already experiencing heavy mortality in the northern and eastern parts of the state due to beech bark disease, a

non-native disease complex caused by a combination of an insect and a fungus (Houston and O'Brien 1983). Climate change may exacerbate this problem by increasing the stress on the species.

Black cherry is the third most common species in Pennsylvania (McWilliams et al 2007), and it is found throughout the state. The best black cherry habitat is currently found in the western part of the state. Under the cooler scenarios, the best habitat for this species shifts to the northern and higher parts of the state. Even under the warmest scenarios, suitable habitat for the species is projected to be found throughout the state, but the species' area-weighted importance values are reduced by 81 to 91 percent. Black cherry is currently the most valuable commercial species in the state, and its loss would be a substantial blow to the state's hardwood lumber industry. Suitable habitat for striped maple is currently found in the central and northern highlands of the state. As the climate warms, its suitable habitat is projected to shrink, but it is still projected to be found in a narrow north-south band in the central part of the state.

Like most of the other species in this second category, the most suitable habitat for eastern hemlock is currently found in the northern part of the state and areas with higher elevation. Currently the sixth most common species in Pennsylvania (McWilliams et al 2007), the importance values of the habitat for this species are projected to decline, but its range is not projected to shrink substantially, even under the high-emissions scenarios. However, this species is currently under attack in the southeastern half of the state from the hemlock wooly adelgid, an exotic insect that feeds on the trees, causing hemlocks to decline and die over several years (McClure et al. 2001). The range of the hemlock wooly adelgid continues to spread to the west and the north. Increased stress from climate change will likely make hemlocks more susceptible to attacks by the adelgid. Eastern hemlock is no longer a valuable timber species, but it has significant ecological and aesthetic value. Hemlocks often grow in the lower, wetter areas along streams, and their dense shade helps to maintain the colder stream temperatures that brook trout and other native fishes are adapted to. The species' dense foliage provides cover for a variety of wildlife species, including the black-throated warbler, the solitary vireo, and the northern goshawk, all of which are dependent on hemlock forest habitats. Hemlocks are also widely used as landscaping trees in urban and suburban environments.

The importance values of the species in the next category – red maple, sugar maple, eastern white pine, sweet birch, white ash, and American basswood – are projected to decline moderately (8-35 percent) under the cooler scenarios and substantially (54-82 percent) under the warmer scenarios. This group includes four of the seven most common species in the state. Red maple is currently the most common tree in Pennsylvania (McWilliams et al. 2007). It is found throughout the state but is more prevalent in the higher, more northern areas. Red maple has been increasing its dominance in the state for the past several decades. Abrams (1998) describes the species as a "supergeneralist" that thrives in a wide variety of environmental conditions. He hypothesizes that historically the species was limited primarily by frequent fires, often set by Native Americans and early European settlers. Red maple has dramatically expanded its habitat with the near-elimination of fire from Pennsylvania's forests in the 20th

century. While still a relatively low value species, red maple stumpage prices have generally increased more than those of other species, and it is now a moderately valuable timber species (Jacobson and Finley various years). While red maple continues to increase in volume in the state, the number of red maple trees began to decline between 1989 and 2004 (McWilliams et al. 2007) with the declines happening entirely in the smallest diameter classes. This suggests that while mature red maple trees continue to grow and add volume, regeneration of this species is slowing. This would be consistent with the projections in Table 7.1, which show red maple's area-weighted importance values declining by 14-34 percent under the low-emissions projections and by 70-73 percent under the high-emissions projections.

Sugar maple is currently the fifth most common tree species in Pennsylvania (McWilliams et al. 2007). It is one of the most widely recognized trees in the state, known for its attractive and valuable wood, the syrup made from its sap, and its stunning fall colors. Unfortunately, sugar maple has been declining throughout the northeastern US, particularly in northern Pennsylvania, since at least the mid 1980s (Horsley et al. 2000, 2008, Driscoll et al. 2001). This decline has been attributed to repeated defoliations by a variety of insects, including the elm spanworm, drought, soil nutrient depletion attributed to atmospheric deposition, and climate change. Sugar maple is found throughout Pennsylvania, and its range is not projected to change significantly under the cooler scenarios, but the projected area-weighted importance values decrease by 17 to 20 percent. Under the warmer scenarios, however, much of the southern part of the state is projected to become unsuitable for this species, and its importance values are projected to decline by 62 to 82 percent.

Eastern white pine, the tallest tree species in eastern North America, was once one of the most common trees in northern Pennsylvania and even today is found in nearly all parts of the state. Heavy harvesting of the species for ships' masts and its valuable lumber in the 18th and 19th centuries greatly reduced the species' abundance. Recently, the species has been making something of a comeback in the state, with increasing numbers in both large and small diameters (McWilliams et al. 2007). Under the projected climate change scenarios, however, the species' suitable habit is increasingly restricted to the northern and higher-elevation parts of the state and its projected area-weighted importance values decrease by 14 to 22 percent under the cooler scenarios and by 68 to 71 percent under the warmer scenarios.

Sweet birch, also commonly known as black birch, is currently the second most common species in Pennsylvania and the most rapidly increasing in abundance (McWilliams et al 2007). Sweet birch is not adapted to fire and, like red maple, has probably benefited from the success of fire exclusion since the early part of the 20th century. While sweet birch is used for lumber production it is not a high value species, as it seldom reaches a large size and has generally poor form. The habitat suitability projections suggest that the trend toward the increasing abundance of sweet birch in the state may be reversed by climate change, with the species' importance values projected to decrease by 12 to 35 percent under the cooler scenarios and by 63 to 64 percent under the warmer scenarios. Suitable habitat for the species shifts toward the northeastern part of the state.

White ash is currently the seventh most common tree species in Pennsylvania (McWilliams et al. 2007). While ash lumber is used for specialized purposes such as bats and flooring, these uses and the stumpage prices for ash have declined in the past 20 years (Jacobson and Finley various years). Ash is a popular landscaping tree in urban and suburban settings. The habitat projections suggest that climate change will greatly reduce the suitability of the habitat in the state for this species, yet even under the warmer scenarios, the species could potentially be found in all parts of the state. However, a greater threat to the species, and other ash species as well, is the emerald ash borer, an exotic insect that has devastated ash populations in Michigan, Ohio, Indiana and Ontario (McCullough 2009). Experience in those states suggests that once the emerald ash borer becomes established virtually all the ash trees in the area are eventually killed. The insect was identified in the Pittsburgh area in 2005 and in central Pennsylvania in early 2009. It is highly likely that it will eventually kill nearly all the ash trees in the state.

American basswood, the final species in this category, is currently widely distributed at relatively low densities in most parts of the state, except the southeastern and, to a lesser degree, the southwestern corners of the state, where it is not currently expected to find suitable habitat. The species is projected to retreat to the north and the east and the higher elevations as the climate warms. Model projections for this species are less reliable, however.

The next category includes four species – northern red oak, chestnut oak, yellow-poplar, and sassafras – that are currently fairly widely distributed within the state and are projected to either decline only marginally or even benefit marginally in the state under the cooler, low-emissions scenarios, but will generally suffer moderate losses of habitat quality (importance values declining by 20 to 48 percent) under the hotter, high-emissions scenarios. Northern red oak and chestnut oak are currently the eighth and ninth most common species in the state, respectively. In terms of biomass, northern red oak is the third most important species in the state and chestnut oak is the fifth. Both have experienced small declines in their numbers in the past two decades (McWilliams et al. 2007). Their decline is partly due to a general problem regenerating oak species in the eastern US (Lorimer 1993). Northern red oak is projected to decline moderately under either the low-emissions scenarios (11-20 percent) or the high-emissions scenarios (24-32 percent). Chestnut oak is projected to stay about the same under the low-emissions scenarios (-5 to +12 percent) but decline under the high-emissions scenarios (41-44 percent). Yellow-poplar and sassafras are projected to gain (14-45 percent) under the low-emissions scenarios but decline (20-48 percent) under the high-emissions scenarios. The extreme northeastern part of the state does not have suitable habitat for either of these species when modeled under current conditions, and one can see the northward progression of suitable habitat as all of the state is modeled as suitable habitat, albeit at a low level of reliability, for these species under all of the future scenarios.

The six species in next category are projected to find moderately better habitat in the state under climate change. Three of the species – pignut hickory, black walnut, and flowering dogwood – benefit more (58-115 percent) under the low-emissions scenarios than they do

under the high-emissions scenarios (1-81 percent). The other three species in the category – blackgum, white oak, and American elm – tend to gain moderately (-4 to +64 percent) under the low-emissions scenarios and do even better (56-121 percent) under the high-emissions scenarios. The best habitat for most of the species in this category shows a definite shift from the southern part of the state to the northern part of the state. Blackgum is currently the tenth most common species in the state (McWilliams et al. 2007). Blackgum is a medium-sized tree, and is not particularly valuable as a timber tree. It is currently distributed mostly in the southern part of the state. It is projected to benefit moderately (55-59 percent) under all scenarios, but the best habitat for the species is projected to shift further north under the higher-emissions scenarios.

Black walnut trees are highly prized for their attractive, dark-colored wood and their edible nuts. The species is not currently common in Pennsylvania, and is found mostly in the state's southwestern and southeastern corners. Black walnut is projected to gain more under the cooler scenarios, expanding its habitat to nearly all of the state. Under the warmer scenarios the species' habitat is projected to shift out of the southwestern and southeastern parts of the state to the northern and central parts of the state, so although the statewide importance values for the species are about the same under the high scenarios as under current modeled conditions, the species would be found in almost completely different parts of the state. This species also has a relatively low model reliability rating.

White oak is one of the more valuable timber species in the state (Jacobson and Finley various years). While it is only the 15th most common species in the state, it is the eighth most important by biomass volume (McWilliams et al. 2007). White oak is currently found mostly in the central part of the state and is relatively rare in the northern tier of counties. Its range is projected to expand under the low-emissions scenarios and shift to the north under the high-emissions scenarios.

American elm habitat is projected to improve somewhat under the low-emissions scenarios and more substantially under the high-emissions scenarios. However, this tree has already been decimated in the state by Dutch elm disease and is now suffering from a new non-native disease, elm yellows. It is unlikely that this species will be common in Pennsylvania's forests in the future. Flowering dogwood is an understory tree, known for its spring flowers. It is currently found primarily in the southern part of the state. Favorable habitat for the species is projected to expand in the state under the low-emissions scenarios and shift to the northern part of the state under the high emissions scenarios. However, the species has been heavily hit by an exotic fungal disease, dogwood anthracnose.

The next category includes four species that are expected to gain substantial habitat in the state under climate change. Two of the species – mockernut hickory and black oak – are currently somewhat common in southern Pennsylvania. The area-weighted importance values for these species are projected to improve in the state, by 53-116 percent under the low-emissions scenarios and by 140 to 280 percent under the high-emissions scenarios, and their habitats shift into the northern parts of the state. The other two species in this

category – silver maple and eastern redcedar – are currently not common in Pennsylvania and are found mostly in the southeastern part of the state. The habitat for silver maple is not projected to change much under the cooler scenarios, but is projected to expand throughout the state under the warmer scenarios. Suitable habitat for redcedar is projected to expand considerably under the cooler scenarios and throughout the state under the warmer scenarios. Model reliability for these two species are relatively low.

The final category includes eight species – loblolly pine, shortleaf pine, common persimmon, red mulberry, black hickory, blackjack oak, winged elm, and post oak – that are currently rare in Pennsylvania, but that are projected to gain substantial habitat in Pennsylvania. Whether these species will thrive in the state as well as the model projects is less certain than for species in other categories in Table 7.1. The statistical model reliability for three out of eight species in this category is either medium or low, and Peters et al. (2008) question the reliability of the projections for winged elm, black hickory and post oak, even though these species are given a high statistically-based model reliability rating. Shortleaf pine and loblolly pine are southern pine species with very little suitable habitat in the state under current conditions. Under the low-emissions scenarios, suitable habitat for shortleaf pine is projected to expand to most of the southern half of the state, with the exception of the Laurel Highlands region. Loblolly pine is projected to expand its range but remain mainly in the coastal plain of the southeastern portion of the state. Under the high-emissions scenarios, all of the state is projected to become suitable for shortleaf pine and importance values increase dramatically. Loblolly pine expands its range to all but the northern tier of counties and increases its importance values dramatically in the state's southeastern corner. Foresters have considerable experience managing these species in plantations, and rotations for these species are relatively short (2-4 decades), so it is quite plausible that these species could be widely established in the state by the end of the century.

Whether or not the remaining species in this category will become widely distributed in Pennsylvania is more speculative. Winged elm is susceptible to elm yellows disease, so it is not likely to be common in the state in the future. Post oak and black oak are likely to be more limited by soils than reflected in the models (Peters et al. 2008), and in general oaks and hickories are currently difficult to regenerate in much of the eastern US, including Pennsylvania, even when they are already present (Lorimer 1993). Persimmon and mulberry are not particularly valuable species for their lumber, so it is unlikely that large areas will be planted in those species.

In summary, the eight most common species in Pennsylvania – red maple, black birch, black cherry, beech, sugar maple, eastern hemlock, white ash and northern red oak – are all projected to lose habitat to varying degrees in the state under climate change. Most of these species are associated with the northern hardwood (maple-beech-birch) forest type, which is currently modeled as the dominant forest type in the state (Figure 7.1). Under the low-emissions scenarios, the area dominated by this forest type is projected to shrink, but it remains the dominant forest type in the state. Under the high-emissions scenarios, however, this forest type is projected to disappear from the state, and even from much of

New York and New England as well. Thus, it seems likely that northern hardwood species will lose habitat and become less abundant in the state under climate change.

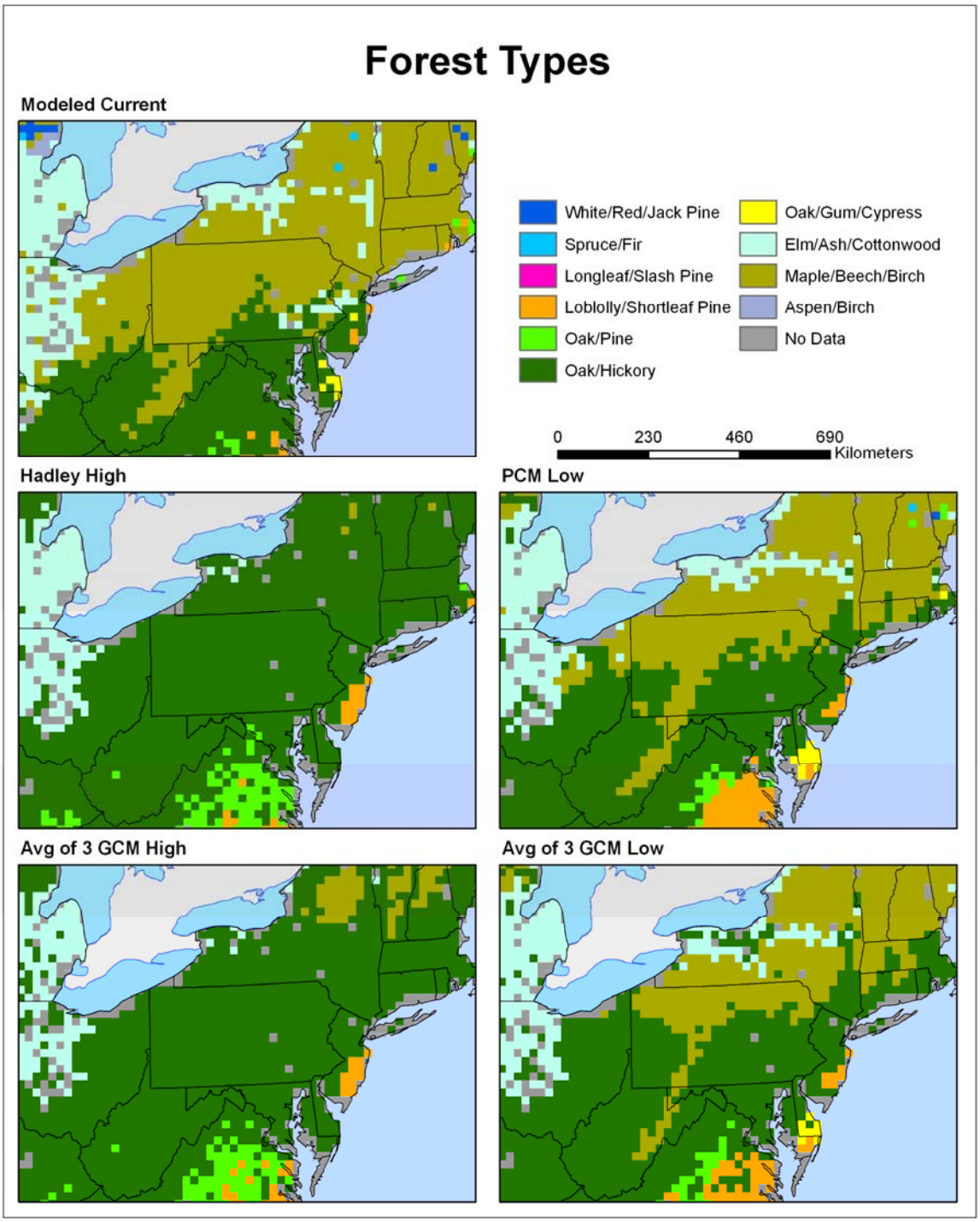

Figure 7.1. Current modeled forest type distribution in Pennsylvania and surrounding states and projected forest type shifts under four climate change scenarios (image provided by Louis Iverson and Matt Peterson).

The extent to which this will occur, however, is highly dependent on the level of emissions over the coming decades and the degree of climate change that occurs.

Species that are predicted to gain habitat in the state are oaks, hickories and southern pines. The oak-hickory forest type that currently occurs primarily in the southern part of the state is projected to expand its area under the low-emissions scenarios and completely dominate the state under the high-emissions scenarios (Figure 7.2). Whether and how this will occur is less certain, however, given current difficulties establishing oaks and hickories throughout the eastern US (Lorimer 1993). Oak is typically established using natural regeneration techniques that rely on the presence of an existing seed source. The large tap root that helps give oak its ability to survive (and even thrive) with fire also makes it a relatively difficult species to establish in plantations (Johnson et al. 2002). Furthermore, oaks and hickories are generally managed on longer rotations (60-100 years), which make large investments in stand establishment unprofitable in most situations. Finally, oaks and hickories are fire-adapted species, and prescribed fire is difficult to apply in landscapes with high human populations (such as much of Pennsylvania). Southern pines are also projected to find increasingly suitable habitat in Pennsylvania. Southern pines are commonly managed in plantations and their cultivation is relatively profitable, so it seems reasonable that large areas of the state – primarily in the south and in lower elevations – could eventually be converted to pine plantations. Black walnut is another species that is projected to find improved habitat in Pennsylvania under climate change. Because of the high value of its wood, black walnut is cultivated in other parts of the country, and it may become feasible to profitably grow high-quality black walnut in Pennsylvania if the state's climate warms as projected by the GCMs.

The techniques used to project changes in the potential suitable habitat resulting from climate change for tree species are sophisticated and well-grounded in volumes of relatively high-quality data. They represent the most robust scientific, data-based projections available today of how tree species are likely to respond in the coming decades to the changing climate. Yet it is also important to bear in mind their limitations. First, it is well known that trees live and often thrive outside the ranges where they have historically been found. Thus, there are factors other than climate that limit species' ranges, so they may not be as sensitive to changing climates as these models predict (Loelhe and LeBlanc 1996). Furthermore, projections of future distributions are based on the outputs from GCMs, which, again, embody significant uncertainties about how the global climate will respond to atmospheric changes. In addition, the habit projection models discussed here assume that current species distributions are in equilibrium with the current climate. While climates have been relatively stable for the past 1,000 years, the climate has changed over the past 50-plus years, and current tree distributions likely have not had time to respond to this. Furthermore, over the past century and a half humans have radically influenced the current distribution of tree species in the eastern US, through harvesting, fires, fire exclusion, changing wildlife populations (e.g., increased deer populations), pollution, introduction of exotic pests and diseases, planting and other activities.

Potential suitable habitat models may also underestimate the sensitivity of tree species to climate change. Another factor that is not accounted for in the species habitat projections is genetic variation within species. For example, black oak is currently found from southwestern Maine to eastern Texas. However, it is possible that the black oaks that are currently found in Texas and adapted to that state's climate are genetically quite different from those that are currently found in Pennsylvania. Black oak is projected to benefit in Pennsylvania as the state's climate warms. Nevertheless, it is possible that the black oaks that are currently found in Pennsylvania will not thrive in the state under climate change and that it will be necessary to plant black oaks that are currently adapted to a more southern climate than Pennsylvania's, even though the species as a whole is projected to do well in Pennsylvania under climate change. If this is true of many species, even for species that are projected to do well in the state, it may be necessary to bring nursery stock into the state from southern provenances in order to ensure that the future forest will be able to thrive under a changed climate.

7.1.2 Increased Susceptibility to Disturbances

Trees adapt to both the climate where they are found and the disturbance regime they have evolved under. Disturbance regimes, in turn, depend on both the climate and the structure and composition of the forest ecosystem. Trees tend to live a long time and they are unable to move to adjust to changing climates. Pennsylvania's trees are likely to experience a significantly changed climate within their lifetimes with little ability to adapt to those changes. As a result, Pennsylvania's forests will likely become increasingly stressed as the climate changes. This stress could create conditions that may foster increased rates of disturbance, including higher mortality rates, increased fuel loads, and greater susceptibility to insect and disease attacks (Dale et al. 2001). Unlike trees, disturbance regimes can change relatively rapidly in response to changing climatic conditions. Increased availability of stressed trees, combined with warmer and possibly wetter conditions could favor higher rates of insect and disease outbreaks. Increased fire risk and larger fires have already been attributed to climate change in the western US (Westerling et al. 2006), but not in the more humid eastern US. Warmer weather, prolonged periods of drought and increased quantities of dead wood could, however, create conditions where forest fires could be more common in Pennsylvania. Increased total rainfall and potential CO_2 fertilization effects could create higher fuel loads, which during periods of drought could result in greater susceptibility to fire (Dale et al. 2001).

Some insects and diseases will likely benefit from climate change, just as some tree species will benefit. Insect populations have the potential to respond dramatically and rapidly to climate change. Because they are cold-blooded, they are particularly sensitive to changing temperatures. Additionally, they typically are mobile, they have the capacity to rapidly increase their populations, and, because of their relatively short generations, they have the potential to adapt genetically to changing environments (Logan et al. 2003). Bark beetles in the western U.S. have benefited from longer growing seasons, resulting in outbreaks that have killed millions of acres of spruce and pine. In the East, it is believed that the spread of the hemlock wooly adelgid has been slowed by cold winter temperatures, so climate change may allow the insect to spread farther and more rapidly

than what has been observed to date (Paradis et al. 2008). Furthermore, climate change could promote expansion of invasive species into more remote high-elevation areas which currently tend to have less problems with invasives (Pauchard et al. 2009).

Invasive plant species may also benefit from climate change. Ziska (2009) studied the growth response of six invasive weed species, including kudzu and Canada thistle, to increased atmospheric CO_2 concentrations and found that their growth rates increased more than three times faster than similar CO_2-induced growth increases for other plants. Smith et al. (2000) also observed that elevated CO_2 levels benefited an invasive, exotic grass more than native plants in a western North American ecosystem.

7.1.3 Changing Productivity

Several studies indicate that climate change will most likely lead to an overall increase in the net primary productivity (NPP), and hence growth rates, of the earth's ecosystems. In fact, Nemani et al. (2003) estimated that global NPP has already increased by 6 percent just between 1982 and 1999. This is due to a host of factors related to climate change, including longer growing seasons, increased temperatures, increased rainfall, reduced cloud cover, and CO_2 fertilization. Experimental studies of these effects include free-air CO_2 enrichment (FACE) studies, open-top chamber (OTC) and growth chamber (GC) studies (Luo et al. 2006). Luo et al. (2006) combined the results of over 104 published papers and concluded that average carbon pools in shoots, roots and whole plants increased by 22.4 percent, 31.6 percent and 23 percent, respectively, under higher CO_2 concentrations. Woodward (2002) also provides a useful review of CO_2 fertilization studies. Norby et al. (2005) report that four FACE sites (which most closely replicate likely natural conditions of trees growing in natural conditions) located in forests with different productivity levels averaged 23 percent increases in NPP under elevated atmospheric CO_2 concentrations. Increases in NPP can be short-lived or non-existent, however, if increases in plant growth rates are limited by other factors, such as soil fertility (Körner 1993, Oren et al. 2001, Hungate et al. 2003). At one relatively infertile site reported by Oren et al. (2001) increased CO_2 levels had no effect on growth. However, when nitrogen fertilizer was added to the infertile site in combination with elevated atmospheric CO_2 concentrations substantial improvements in growth rates were observed. At the FACE sites, NPP increases in the forest ecosystems were not limited by nitrogen uptake because of increased plant C allocation to belowground structure and improved soil nitrogen acquisition (Finzi et al. 2007). The long-term fate of the increased carbon acquisition by forests remains uncertain because of high variability in where the carbon is stored in the ecosystem and broad range in C turnover rates for leaf area, stem wood, and coarse and fine roots.

Increased net growth rates may not be realized for some time, since trees that are no longer well adapted to the climate where they are growing will likely become stressed and suffer higher mortality rates. Furthermore, changes in species composition in response to climate change can also result in both increases and decreases in growth rates (Chiang et al. 2008).

7.2 Impacts on biodiversity and ecosystems

There is considerable research indicating that climate change is already affecting ecosystems. Over the past 3-4 decades changing climates have caused shifts in species' ranges and phenology – i.e., the timing of key events such as migration, bud break and flowering. Far too many studies have identified such changes in individual species and groups of species to review them all here. Three such studies are noted here because of the large number and/or variety of species covered. Parmesan and Yohe (2003) considered changes in the ranges and timing of key springtime events for over 1,700 species and found average range shifts of 6.1 km per decade toward the poles and that spring events are occurring on average 2.3 days per decade earlier. Similarly, Root et al. (2003) considered 143 studies of biological changes driven by climate change and found that more than 80 percent of the species studied exhibited shifts in their ranges, timings of events, morphologies, behaviors and genetic frequencies that were consistent with warming temperatures (e.g., range shifts toward the poles or to higher elevations or earlier spring breeding times). Finally, Hickling et al. (2006) assembled range data for 329 species from 15 taxonomic groups that occur in Great Britain and found that the ranges of 275 species had shifted northward while only 52 had shifted southward.

In general, climate change affects There are many uncertainties about how ecosystems will be affected by climate change in the future. However, it is likely that ecosystems will be more negatively affected than human systems, simply because humans are one of the most adaptable species on the planet – humans are, after all, found in virtually every biome. Projected unprecedented rates of climate change will require all species to adapt, and those that are most adaptive will likely end up as "winners" and those that do not adapt well will tend to be "losers." To the extent that climate change leads to increased extinction rates, however, we will all be at least somewhat poorer. Several studies (Schwartz 1992, Berry et al. 2002, Hannah et al. 2002, Midgley et al. 2002, Peterson et al. 2002, Thomas et al. 2004) suggest that climate change could drive a large number of species to extinction. Whether or not a species goes extinct as a result of climate change depends on several factors: 1) how broad the current range of the species is, 2) how narrow the habitat requirements of the species are, 3) the mobility of the species, and 4) the adaptability of other species that the species is dependant on (Peters and Darling 1985, Schwartz et al. 2006). In general, plants tend to be less mobile than animals, and plants with the most narrow habitat requirements are the most likely to suffer high extinction rates as a result of climate change. Birds and insects tend to be the most mobile, but if their habitats are not wide-ranging or if they do not migrate with the changing climate they could also go extinct. Many popular wildlife species, such as deer, on the other hand, are mobile generalists and are relatively unlikely to go extinct.

Because there are so many interacting factors, predictions for individual species are very difficult to make with any certainty. Rodenhouse et al. (2009) reviewed a wide range of studies of how climate change has and might affect the wildlife currently found in the forests of the northeastern U.S. and eastern Canada. While they considered a wide range of species, including mammals, birds, insects and amphibians, because the sheer number and variety of species in each group and the variety of ways each can be affected by

climate change, their observations only illustrate the range of possibilities of how wildlife can be affected by climate change. For example, temperature and rainfall regimes affect insect populations, which in turn affect the animals that depend on those insects for food. Winter temperatures affect hibernation survival for species such as bats in unexpected ways; for example, warmer temperatures can increase energy requirements by causing more arousals during the winter. Changes in the timing of the hatching of caterpillars that were once timed to match bud break on favored host trees sometimes do not match, resulting in less food availability for the caterpillar – good for the host tree but bad for the caterpillar. Frog species that now hatch earlier than other species find more food availability than those hatching later and thrive while those hatching later decline. Again, all these changes and their interacting effects are very hard to predict.

Models are an important tool not only for both predicting the general risk of extinctions for an area and for quantifying the uncertainty. For example, Malcolm et al. (2006) generate predictions of extinction rates for 25 biodiversity hotspots under several GCMs and under two global vegetation models, with different assumptions about migration rates, biome specificity, species' habitat specificity, and species-area relationships. Their projections range from no extinctions to losses of up to 75 percent of the species in the biome.

It is very possible that climate impacts on Pennsylvania's forest ecosystems will be substantial in the 21st century. This is due to the likelihood of significant shifts in the species composition and character of Pennsylvania's forests. As noted earlier, Pennsylvania's eight most common species are projected to decline in the coming century. Additionally, disturbance rates from insects and diseases and from fire are likely to increase. These shifts are likely to be accompanied by a shift from natural to cultivated forests as many of the species that are currently present in the state find the habitat here increasingly less suitable and natural regeneration becomes increasingly more difficult and less desirable. A shift from natural to planted forest communities will likely lead to simplified forest plant and animal communities (Carnum et al. 2006). Wildlife populations will need to migrate across an increasingly fragmented landscape in order to find more suitable habitat. Furthermore, bioreserves created to protect particular communities of species will no longer support those communities (Peters and Darling 1985).

7.3 Economic Impacts

While the implications of climate change for ecosystems are almost certainly negative, the economic implications could be either positive or negative. In looking at the economic impacts of climate change on the forest products sector, it is useful to consider the perspectives of three different groups of people: 1) forest landowners, 2) forest products manufacturers (including loggers), and 3) consumers of forest products. Each of these groups will be affected differently by climate change. The main potential impacts from climate change that will affect Pennsylvania's forest products sector are 1) increased mortality due to stresses on trees that are not well adapted to changed climatic conditions and increased disturbance rates, 2) increased forest productivity due primarily

to warmer temperatures, longer growing seasons, increased rainfall, and CO_2 fertilization effects, 3) a need for substantial investments in forest protection and regeneration, and 4) increased demand for forest biomass for energy production.

Pennsylvania's forest products industry operates in a global market. Thus it is not possible to project the industry's fate without considering likely scenarios for the global market for forest products. While the U.S. and Canada remain the largest producers of pulp and paper in the world, for the past 20-plus years, the global paper market has seen a shift out of Canada, the U.S. and Europe (primarily Scandinavia) to Asian and Latin American countries such as China, Brazil, Indonesia, Russia, Malaysia and Chile. With faster potential forest growth rates, rapidly expanding areas in plantations, fewer environmental restrictions, favorable exchange rates, and low-cost labor, these countries production costs are considerably lower than U.S. and European producers' costs. As a result, some 72 pulp and paper mills were closed in the U.S. between 1997 and 2002 (AFPA 2002). Pennsylvania has experienced a similar trend, losing roughly half of its pulp and paper capacity during the past 20 years. These trends are not likely to be reversed in the coming decades.

Pennsylvania's niche in global forest products markets has been the production of high-quality hardwood lumber and veneer. The state's current favorable position in these markets is the result of the fortuitous regeneration of a high-quality cherry, maple and oak forest following the devastation of the state's period of forest exploitation in the late 1800s and early 1900s. This resource began to reach maturity in the 1980s and has continued to grow and mature for the past 20 years. However, the long-term sustainability of this resource is far from assured, as it is threatened by a host of problems already identified in this report, namely unsustainable harvest practices, regeneration problems, invasive pests and pathogens, and climate change. In the coming decades this resource is likely to continue to be harvested and utilized. Increased mortality rates due to either the primary effects of a changing climate or the secondary effects of increased disturbance rates may accelerate this harvest, but unless the mortality occurs in a sudden event such as a hurricane, a severe drought, or a major pest outbreak, forest products manufacturers will not likely be negatively affected, they may even benefit from accelerated harvesting opportunities. Similarly, forest products consumers are not likely to be negatively affected; they may even benefit from lower forest product prices. Forest landowners, on the other hand, may suffer from lower prices from selling salvaged dying or dead timber. Thus, in the short run, forest products manufacturers and consumers may benefit from higher mortality rates from a changing climate while forest landowners will be the losers.

What happens in the long run depends on what happens after the current generation of forests is harvested. If little attention is paid to regeneration of these stands after harvest, the state may end up with millions of acres of poorly stocked forests with low-value species that are not well adapted to the changing climate. Such forests will not produce high-value products, and they will not provide high-value ecosystem services. There will be very little incentive to keep these acres in forest. Even if landowners and forest managers are careful to regenerate currently desirable species on these lands, these

species may turn out to be poorly adapted to future climatic conditions. On the other hand, if species and genotypes can be identified that will thrive under future climatic conditions, and if the investments are made to establish these species, then future growth rates on those sites may exceed current growth rates. This would benefit forest landowners, the forest products industry, and forest products consumers. The key challenges, therefore, for forest managers are to identify species and genotypes that will be well adapted to the state's future climate and to find the resources to regenerate harvested sites with these species. This would require a major shift in silvicultural thinking in the state, as it would, in many cases, entail a shift from natural regeneration to artificial regeneration, i.e., plantations. This is a significant challenge, and, since the stands we are regenerating today will be around for time scales of several decades to more than a century, this is a challenge we must begin to address today if we want to have healthy forests and a healthy forest products industry in the state several decades from now.

Increased demand for woody biomass could potentially be helpful in achieving a more desirable future for the forests of Pennsylvania. Woody biomass markets are an opportunity for forest landowners, as they would provide a market for low value species and trees that are today mostly a liability for landowners, as they often cost more to harvest than what they are worth. Having a market for this so-called "low-use" wood makes a larger variety of silvicultural management options financially viable.

Unfortunately, the future outlook for one of the culturally important products of Pennsylvania's forests today, maple syrup, looks bleak. Consumers of maple syrup will most likely continue to find the product, however, as it will likely continue to be produced in regions north of Pennsylvania.

7.4 Role of Forests in Mitigating Climate Change

Forests can play a role in mitigating the factors causing climate change. Forests – and their soils – represent one of the largest terrestrial pools of carbon. Furthermore, they actively sequester carbon from the atmosphere. However, at current growth rates, the carbon sequestered by Pennsylvania's forests each year equals only one twentieth of the carbon emissions from burning fossil fuels in the state (Pa. DCNR 2008a). Even if growth rates could be doubled, which is unlikely, sequestration by forests would only offset one tenth of our emissions. It is possible to significantly increase the rate at which carbon is sequestered by the forests of Pennsylvania, but not without very large investments in forest management, and not without fundamentally changing their character, from the naturally-regenerated forests typical in Pennsylvania today, to planted forests.

On the other hand, forest clearing results in losses from the pool of carbon stored in the forests and their soils. Depending on what happens to the wood from cleared forest land and depending on the land use that replaces forest, much of the carbon stored in this pool will be emitted to the atmosphere. Thus, preventing the loss of forests can be an effective way to reduce carbon emissions. Globally, forest clearing has been the second most

important source of carbon emissions to the atmosphere, after burning fossil fuels (IPCC 2007). In the eastern US, and in Pennsylvania in particular, the pool of carbon in forests has increased over the past century. However, this trend may be reversed as forestland is increasingly cleared for development and as growth rates decline and harvest levels increase as the forest matures (McWilliams et al. 2007). The most effective policy to ensure the continued contribution of Pennsylvania's forests to mitigating climate change is for them to remain forests.

In general, it is possible to dramatically increase forest growth rates, and hence carbon sequestration rates, but this typically requires a shift from natural forests to intensively-managed plantations. In temperate climates like Pennsylvania's, this would generally involve planting conifers. Pennsylvania's climate and soils are not well-suited to this type of forestry, which is why such plantations do not currently exist in the state. Rather, Pennsylvania's forests have been managed for the state's native oaks and northern hardwoods. These forests are relatively slow growing, but produce high-quality, high-value wood products, albeit over long rotations. They are not particularly responsive to silvicultural treatments to increase their growth rates, and the practice of silviculture in the state has focused more on increasing the quality of wood grown through improvement thinnings and, more recently, on addressing the challenges of regenerating the forest with ecologically and economically desirable tree species. Where good silviculture has been practiced, the opportunities for increasing sequestration rates are relatively limited.

On the other hand, because roughly 70 percent of Pennsylvania's forestland is privately owned (McWilliams et al. 2007), and because Pennsylvania's private forest landowners do not have a strong tradition of seeking professional forestry assistance when making management decisions, much of Pennsylvania's forestland has been poorly managed. For example, diameter limit cutting is widely practiced. Because Pennsylvania's forests were, for the most part, regenerated after complete clearing, often followed by fire, all of the trees in a given stand are often more-or-less the same age. As a result, when the larger trees are harvested, rather than removing the older, mature trees, as landowners often mistakenly believe, it is the fastest growing, genetically superior, and economically most valuable trees that are being removed. The residual trees are typically slower growing, genetically inferior, and economically less valuable, resulting in a forest that is understocked, relatively slow growing, and economically less valuable. Repeated application of this harvesting approach eventually leaves the landowner with few financially viable silvicultural options. Growth rates could be significantly increased in these forests, but often only by clearing the existing forest and starting again with planted trees. This management option is expensive and will not provide financial or significant carbon sequestration benefits for a decade or more. Nevertheless, because of the other ecological and social benefits provided by healthy forests, this could be a worthwhile investment from society's perspective.

Pennsylvania has tens of thousands of acres of what are termed "marginal lands" that are not currently forested or have trees but at very low stocking levels. These include marginal farmland, land that is idle because of lack of management by the current owner, and reclaimed mine lands. Trees could be planted in these areas, again at some expense,

and they would eventually sequester significant amounts of carbon, but not for the first decade or so. Thus, there likely are more cost-effective ways to sequester carbon, with more immediate effects, than afforestation efforts on these lands. Urban and suburban environments offer another important opportunity for increased carbon sequestration by trees. In addition to sequestering carbon, urban trees save energy by reducing cooling costs, absorb other pollutants, increase property values, calm traffic, and improve the aesthetics of urban and suburban environments. Because of these substantial co-benefits, planting urban and suburban trees is likely a cost-effective approach to sequestering carbon, but, again, compared to the total carbon emissions of our society, the amount of carbon that urban trees can sequester is relatively small.

Mortality caused by native and non-native diseases and pests also significantly reduces the carbon sequestration rates of Pennsylvania's forests. As discussed above, climate change is likely to exacerbate these problems. Investments to mitigate these forest health problems can help to ensure that the state's forests continue to sequester carbon at their highest potential.

Wood from Pennsylvania's forests can be used to produce biofuels that can be used in the place of fossil fuels. This reduces net carbon emissions because the carbon that is released by burning the wood or the biofuels made from the wood is offset by the carbon that is sequestered by the trees when the wood is grown. Wood can be burned directly, co-fired with coal, or converted to biofuels, such as cellulosic ethanol and other advanced biofuels. Biomass conversion is the only currently feasible alternative to fossil fuels for producing liquid fuels. Woody biomass has important advantages over other sources of biomass as it does not directly compete with food production, although it could compete if significant areas of land were shifted out of agriculture into woody biomass production. Furthermore, woody biomass is already available in large quantities in Pennsylvania (Pa. HDC 2008) and the infrastructure for harvesting it and transporting it already exists to some degree. Markets for woody biomass could improve forest management by providing a way for landowners to economically dispose of low-value wood that cannot currently be harvested economically. This would make treatments such as improvement thinnings more economically viable and reduce incentives to only harvest the high-value trees and leave low-value trees to dominate the future forest. While conversion of wood to biofuels such as ethanol is feasible, it is not currently commercially viable. However, substantial investments in research on conversion technologies are likely to lead to commercialization of the technology within the next few years. At least one commercial-scale biofuels facility that will use wood is currently being built in Michigan, albeit with substantial federal and state subsidies (Clark 2007).

A significant challenge with increasing the use of wood biomass for energy is the cost and logistics of harvesting and transporting large amounts of wood to a wood-burning facility or a biofuels refinery. Because the harvesting and transportation costs are a significant part of the cost of producing energy from woody biomass, the most efficient opportunities may well be small-scale uses such as heating or combined heat and power generation for homes, schools, hospitals, or even communities. Another potential problem is that removing too much biomass during harvesting could negatively affect

forest soils through compaction or exporting too many nutrients. These problems can be minimized by putting into place guidelines on how biomass harvests should be done (e.g., Pa. DCNR 2008b).

Finally, forests can be used to mitigate climate change by providing building materials that provide a long-term storage pool of carbon and that require less carbon emissions to manufacture than alternative building materials such as steel, concrete, brick and aluminum (Lippke et al. 2004).

7.5 Adaptation Strategies

There is little doubt that the impact of climate change on forests can be mitigated by efforts to reduce carbon and other greenhouse gas emissions to the atmosphere. Nevertheless, regardless of the success or lack thereof of these efforts, Pennsylvania's climate is likely to change in the coming decades and the state's forest ecosystems are going to be affected by these changes. Since the specific nature of these changes is uncertain, foresters will have to take an adaptive approach to addressing these impacts. Such an approach could include the following strategies:

<u>Invest more in managing for healthy, resilient forests with a high degree of biodiversity</u>. Healthy, diverse forests will be more resilient and more able to adapt to changing climatic conditions. Key steps to fostering healthy forests in the state include:

- Aggressively combat invasive species to eliminate them where possible or at least reduce their spread.
- Continue and increase research to address the state's forest regeneration problem.
- Maintain deer populations at a level that is commensurate with the forest's ability to provide forage for a healthy deer population.
- Educate and encourage forest landowners to use harvest practices that maintain the genetic quality and diversity of the forest resource.
- Minimize forest loss and maintain or increase the connectivity of the forest land base.
- Reduce air pollution and atmospheric deposition of pollutants.

<u>Recognize potential climate-change induced impacts when planning forest management activities</u>. Forest management activities leave their mark on the landscape for decades, if not centuries. Today's forest management activities are creating the forest of the future, so it is important to consider the climatic conditions that the forests we are creating today will experience. While it is difficult to predict exactly what the future climate of the state will be like, foresters must consider what is most likely. To accomplish this, forest managers and policy makers should:

- Support research to better predict climate change impacts on forests.
- Monitor the health and productivity of the forest resource to better detect the impacts of climate change.

- Grow more southern species in state nurseries and obtain seed and other reproductive material from more southern sources.
- When planting, favor seed sources from southern locations over seed from more northerly locations.
- Educate forest managers and policy makers about what is known about climate change and its likely impact on Pennsylvania's forests so they can better account for potential climate change impacts in their management decisions.
- Support research to better understand how to adapt Pennsylvania's forests under a changing climate.

7.6 Conclusions

Forests once covered more than 90 percent of Pennsylvania's land area, and even today they are the state's dominant land use, covering some 58 percent of the state (McWilliams et al. 2007). Pennsylvania's forests contribute much to the state, from forest products and places for recreation to ecosystem services such as providing wildlife habitat and clean water. These ecosystems have been dramatically changed in the past 200 years by extensive clearcutting between 1880 and 1920, fires that burned as much as one million acres a year in the early part of the 20th century, heavy deer browsing for much of the past 70 years, fragmentation, pollution, and invasive non-native plants, insects and diseases. As a result, the state's forests today are very different from the forests the early European settlers found several centuries ago. And many of these problems continue to stress the state's forests.

Climate change will likely cause many additional changes in Pennsylvania's forests. First, the state will become increasingly unsuitable for many of the trees species that are now present, especially those generally associated with northern hardwood ecosystems. Northern species such as paper birch, quaking aspen, bigtooth aspen, and yellow birch are projected to be extirpated in the state under high emissions scenarios, and greatly reduced, if not eliminated, even under the low emissions scenarios (Iverson et al. 2008a). Other species, including American beech, black cherry, striped maple, eastern hemlock, red maple, sugar maple, eastern white pine, sweet birch, white ash, and American basswood, are projected to find increasingly less suitable habitat in the state and will likely decline in numbers. In general, the state is projected to become increasingly hospitable for more southern species such as oaks and hickories, although the state's two most common oaks, northern red oak and chestnut oak, are projected to decline under the high-emissions scenarios. The state will also become increasingly suitable for some species that are currently rare or not present in the state, such as loblolly and shortleaf pines, common persimmon and red mulberry, although it is not clear how these species will come to the state without human intervention.

The warming climate will cause susceptible species to become increasingly stressed, and their mortality rates will increase and their regeneration success will decline, resulting in declining populations in the state of those species. The increasing stress due to climate change will also make some species more susceptible to a host of other stressors,

including atmospheric deposition and both native and non-native insects and diseases. Tree mortality could rise due to these secondary impacts, and it may be difficult to attribute these changes directly to a changing climate. Tree mortality could also increase if climate change increases the frequency of severe storms, and fires may become more common as temperatures rise.

Some studies suggest that the longer growing season, warmer temperatures, possibly higher rainfall, and a phenomenon termed "CO_2 fertilization" will increase overall forest growth rates in the state. However, these effects will likely be offset by increased mortality rates, at least until the climate stabilizes and the mix of tree species in the state is once again in a more stable equilibrium with the state's climate.

The state's forest products industry will need to adjust to the changing resource, but humans and their activities tend to be more adaptable than ecosystems. The industry could benefit from planting faster-growing species and from salvaging dying stands of trees. On the other hand, if mortality is dramatic and sudden, as might occur with an extended drought or a major storm such as a hurricane, the industry might not be able to utilize all of the dead wood. Substantial investments in artificial regeneration may be needed if large areas of forests begin to die back due to climate-related stress.

Forests can contribute to the mitigation of climate change by sequestering carbon. While it may be difficult to substantially increase the growth rates of Pennsylvania hardwoods, additional carbon can be sequestered and stored in the state's forests by increasing stocking levels or reducing stocking reductions, especially those due to poor management practices such as diameter limit cutting. Marginal lands, such as abandoned mine lands, can be reforested, but, again, the best opportunities may lie in preventing forest loss, rather than increasing the number of forested acres. Since 70 percent of Pennsylvania's forests are privately owned, often in small, family-owned parcels, it will be necessary to engage private forest landowners if significant changes are to be made in how Pennsylvania's forests are managed. Forests can also be a significant source of biomass for either direct burning or conversion to biofuels. Biomass is the only currently viable alternative to fossil fuels for producing liquid fuels, and biomass production from forests does not directly compete with food production.

There is little doubt that Pennsylvania's forest ecosystems are going to be affected by climate change in the coming decades. However, there is much the state can do to mitigate and adapt to these changes. They include:

- Invest more in managing for healthy, resilient forests with a high degree of biodiversity.
- Support research to better predict the impacts of climate change on the state's forests.
- Monitor the health and productivity of the forest resource to identify and detect the effects of climate change.
- Recognize potential climate-change induced impacts when planning forest management activities.

Most of these strategies will provide benefits regardless of how dramatically the state's climate changes.

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8.0 Aquatic Ecosystems and Fisheries

Aquatic resources of Pennsylvania are primarily freshwater, and are a significant natural resource. While precise inventory accounts do not agree, the Pennsylvania State Water Plan (2009) presents the following census:

- About 86,000 miles of streams;
- Nearly 4000 lakes, reservoirs and ponds;
- About 80 trillion gallons of groundwater;
- More than 404,000 acres of wetlands; and
- Fifty-six miles of coast along the Delaware Estuary and 64 miles along Lake Erie.

While lakes and coastlines present significant and important habitat and resources, it is the streams and wetlands that are the signature feature of the commonwealth, and are discussed here. These resources are intertwined and dependent upon one another for ecological integrity. For example, the trout population of a headwater stream is dependent upon wetland habitat along its edge. For that reason, we discuss the impacts of climate change on wetlands and headwater streams as a riparian ecosystem, and as representative of the majority of the aquatic ecosystems of the commonwealth.

Pennsylvania's streams and rivers are classified into 124,181 segments by DEP and the Department of Transportation (data from PASDA), and are second only to Alaska in total stream miles in any state. The largest area of stream miles can be found in Ridge and Valley eco-region (21,605 miles), Pittsburgh Low Plateau (14,588), and Allegheny High Plateau eco-region (16,526), as reported in (http://www.dcnr.state.pa.us/wlhabitat/aquatic/streams.aspx).

Nationally, the United States has destroyed more than half of its original wetlands throughout the past 200 years, leaving approximately 100 million acres, while Pennsylvania has lost an estimated two-thirds of its original wetland acreage. Estimates of the total amount of current wetland area in the commonwealth vary, and are due either to the inclusion of lakes, ponds, and estuarine habitat under the definition of wetlands, or their placement in a separate category. The National Wetland Inventory data, as reported by the Pennsylvania Game Commission, includes this aquatic habitat under the definition of wetland, and reports a total of 729,535 wetland acres found in more than 160,000 wetlands across the state (http://www.pgc.state.pa.us). These occur in two major categories: a total of 146,816 acres are defined as lacustrine (lakes and ponds primarily), and 410,009 acres are defined as palustrine habitat (marshes, etc.). An additional 643 acres of estuarine habitat are located in the southeastern region along the Delaware River. Most of Pennsylvania's wetlands (97 percent) are palustrine (bogs, fens, swamps, shallow pools). Emergent wetlands (marshes, meadows) and shrub swamps comprise 10-20 percent of state wetlands. Generally, natural wetlands are concentrated in northeast and northwestern counties, with more than 50 percent of the wetlands in the state occurring in these areas (Tiner 1990).

8.1 Definition and Description of Ecosystem Services

Wetlands and streams are diverse and productive, and provide a number of tangible and intangible benefits to society and the environment. These goods and services have recently been termed "ecosystem services," and the realization that they are critical for human health and well being (Millennium Ecosystem Assessment, 2005) has heightened the need for assessments that can estimate the level of service provided, detect the impact of human activities (including climate change) on these ecosystem services, and guide us to restoration of these services (Zedler, 2003). The MEA defines four types of ecosystem services, termed regulating, provisioning, cultural, and supporting, that are provided by, or derived from, wetlands and headwater streams (Table 8.1). Many of the ecosystem services most highly valued by society are the regulating ones, including water quality improvement and flood control; provisioning ones such as production of fish and game are also valuable and are more commonly recognized as "habitat". The freshwater wetlands of Pennsylvania represent critical areas of aquatic ecosystem function, serving as nursery areas, sources of dissolved organic carbon, critical habitat, and stabilizers of

Services	Comments and Examples
Provisioning	
Food	production of fish, wild game, fruits, and grains
Fresh water[a]	storage and retention of water for domestic, industrial, and agricultural use
Fiber and fuel	production of logs, fuelwood, peat, fodder
Biochemical	extraction of medicines and other materials from biota
Genetic materials	genes for resistance to plant pathogens, ornamental species, and so on
Regulating	
Climate regulation	source of and sink for greenhouse gases; influence local and regional temperature, precipitation, and other climatic processes
Water regulation (hydrological flows)	groundwater recharge/discharge
Water purification and waste treatment	retention, recovery, and removal of excess nutrients and other pollutants
Erosion regulation	retention of soils and sediments
Natural hazard regulation	flood control, storm protection
Pollination	habitat for pollinators
Cultural	
Spiritual and inspirational	source of inspiration; many religions attach spiritual and religious values to aspects of wetland ecosystems
Recreational	opportunities for recreational activities
Aesthetic	many people find beauty or aesthetic value in aspects of wetland ecosystems
Educational	opportunities for formal and informal education and training
Supporting	
Soil formation	sediment retention and accumulation of organic matter
Nutrient cycling	storage, recycling, processing, and acquisition of nutrients

[a] While fresh water was treated as a provisioning service within the MA, it is also regarded as a regulating service by various sectors.

Table 8.1. Ecosystem services provided by wetlands, as per the Millennium Ecosystem Assessment

available nitrogen, atmospheric sulfur, carbon dioxide, and methane [Mitsch and Gosselink, 2000]. Pennsylvania's streams provide productive and diverse habitats for fish, shellfish, and other wildlife; upstream freshwater reaches provide critical habitat for eastern brook trout and other resident species, and lower reaches provide spawning and nursery habitats for migratory fish species such as alewife, Atlantic sturgeon, and the

federally endangered short-nose sturgeon. Wetlands also are spawning and nursery grounds for fish. In fact, most freshwater fish feed in wetlands or upon food produced in wetlands. Pennsylvania wetland habitat statistics for other types of wildlife are significant; of the 38 species of amphibians, 32 (84 percent) find a home in wetlands the majority of the time. Twenty-five percent (11 of the 41 species) of all reptiles spend nearly 99 percent of their life in wetlands. Approximately 122 species of shore and wading birds, waterfowl and some songbirds perform most of their activities in, on or around water.

While stream ecosystem services (primarily "regulating and supporting") have been described on a regional basis (e.g., Roth et al., 2004, U.S. Environmental Protection Agency 2006), the same in not true for wetlands. For example, in the mid-Atlantic, wetland functional assessments have generally been limited to specific functions and/or a limited number of sites. Habitat functions in wetlands have been described in West Virginia for amphibians and macroinvertebrates (Snyder et al., 2006; Balcombe et al., 2005a, Balcombe et al., 2005b), southeastern Virginia for bog turtles (Carter et al., 1999), and West Virginia and North Carolina for vascular flora (Warren et al., 2004, Rossell and Kesgen 2004). Hydrologic functions are even more rarely described (Moorhead 2001), but the high level of resources necessary to perform studies of this magnitude make them rare. In addition, characterization of specific ecosystem services (or functions) provided by wetlands has only recently advanced to large-scale surveys (for a review, see Kentula, 2007).

While all wetland types serve valuable roles, headwater wetland/stream systems may contribute a disproportionate share to watershed functioning and the larger drainage areas and regional watersheds into which they drain. Brinson [1993] described how headwater streams tend to set the biogeochemical state of downstream river networks. These low-order headwater streams account for 60 to 75 percent of the nation's total stream and river lengths, making their riparian communities extremely important for overall water quality [Leopold et al., 1964]. Lowrance et al. [1997] emphasized the importance of riparian ecosystems along first-, second-, and third-order streams for nutrient abatement, pollution reduction of overland flow, and other ecosystem-level processes in the Bay watershed.

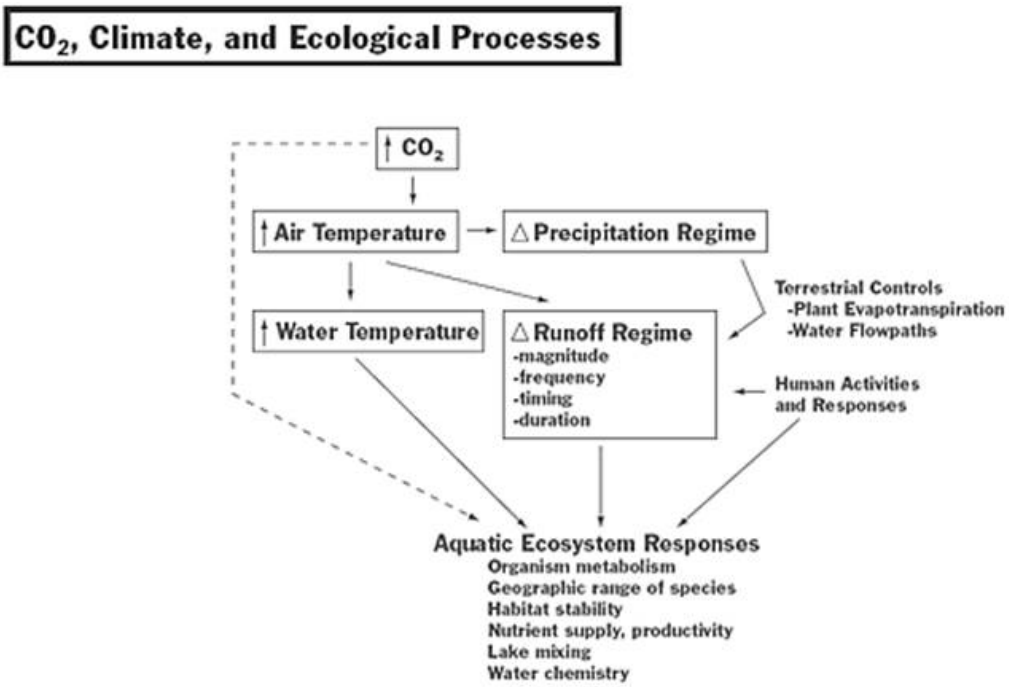
In these systems, the connectivity of the floodplain to the adjacent stream is especially important to the functioning of both communities and all associated downstream systems. Natural patterns of channel and floodplain connectivity sustain resident biota and ecosystem processes such as organic matter accumulation, decomposition, and nutrient cycling [Bayley, 1995; Sheldon et al., 2002]. This lateral and longitudinal connectivity is extremely important for the maintenance of viable populations of aquatic organisms in headwater streams. The loss of stream connectivity to the floodplain can lead to the isolation of populations, failed recruitment, and even local extinctions [Bunn and Arthington, 2002].

While the ecosystems services that are potentially derived from wetlands in good condition are obvious, it is important to note that wetlands form the ecotone and interface

between human activities in uplands and the streams and rivers of large watersheds. Due to this unique landscape position, pollutants and fertilizers from managed portions of the landscape accumulate in these systems, impacting and often impairing their condition, and preventing them from functioning at their highest possible level. Direct modification of wetlands and streams also occurs frequently in the context of agriculture or development, altering habitat structure. Direct appropriation of freshwater for human consumption or agriculture can steal the very water on which these systems depend; this is likely to become a larger problem as populations increase (Postel, 2000; Vörösmarty et al., 2000).

8.2 Major Drivers of Aquatic Ecosystem Response to Climate Change

In order to understand the potential impact of climate change on the production of ecosystem services by streams and wetlands, it is instructive to recognize the major drivers in the production of such services. Watersheds and their freshwater elements are defined by a set of inherent physical factors; climate, soils, geomorphology/topography, and hydrology (Myers et al. 2006, Griscom et al. 2007). Hydrologic processes and patterns, as delivered by regional climate forces and modified by the underlying physical features, fundamentally define and sustain wetlands, streams and lakes. Either directly or indirectly, the ecosystem services provided by these freshwater ecosystems are derived from how water is delivered to and maintained in each type of aquatic resource, as illustrated in Figure 8.1.



Linkages between atmospheric increases in CO_2 and environmental drivers of temperature and precipitation that regulate many ecological processes and patterns in inland freshwater and coastal wetland ecosystems. Solid arrows indicate direct responses; dashed arrow indicates direct effects of lesser known importance.

Figure 8.1. Major drivers in the response of ecosystem services provided by wetlands and streams to climate change processes (from Poff et al., 2002)

While temperature and carbon dioxide levels have direct effects of their own, the clear driver in wetlands and streams are the combined effects of temperature, carbon dioxide, and precipitation on the resulting flow regime (for streams) and hydroperiod (for wetlands). Flow regime and/or hydroperiod are the defining factors in the structure and function of these systems. The amount of water, its rate of flow, and the timing of delivery all significantly determine the type of organisms present, the cycling and removal of nutrients, the occurrence of flooding, the amount of recharge, and the growth and survival of plants and animals. A change in the timing, seasonality, and magnitude of water delivery can severely alter these systems.

Situated at the interface of terrestrial and aquatic systems, wetlands are especially vulnerable to changes in soil moisture regime. Alterations in water sources (ground and surface), along with changes in evapotranspiration, affect wetlands. Most wetland processes are dependent on catchment-level hydrology [Gitay et al., 2001]. Potential impacts range from extirpation to enhancement, and include alterations in community structure and changes in ecological function [Burkett and Kusler, 2000]. Evidence suggests that wetlands depending primarily on precipitation for their water supply may be more vulnerable to climate change than those relying on regional groundwater [Winter, 2000]. The number and complexity of factors that influence wetland occurrence and type make it difficult to predict the fate of wetlands directly from temperature and precipitation changes alone. Needed are predictions of hydrologic shifts induced by both climate and land cover changes. For example, hydrologic impacts due to changes in rainfall patterns will depend on the amount and location of impervious surfaces in the watershed.

While hydrology is paramount, the existing condition (i.e., health) of these systems is a second major driver of their ability to provide ecosystem services. The link between the delivery of ecosystem services and condition lies in the assumption that measures of condition reflect wetland ecosystem processes, which in turn drive the delivery of services. For instance, if condition is excellent (i.e., least-disturbed, or equal to reference condition), then the ecological integrity of the wetland is intact and the provision of services characteristic of that wetland type should occur at reference levels. Climate-induced impacts to wetlands will be layered onto an already compromised resource. An assessment of wetland condition in the upper Juniata River watershed in Pennsylvania [Wardrop et al., 2007b] reported that over 68 percent of the total wetland area was in medium or low condition, correlating with increased agricultural and urban land use in the watershed. Two regional assessments of wetland condition found that the ability of wetlands in both the Upper Juniata (Pennsylvania) and Nanticoke (Delaware) watersheds to perform valuable functions, such as removal of inorganic nitrogen and retention of inorganic particulates, is already significantly reduced [Wardrop et al., 2007a; Whigham et al., 2007]. The majority of these wetlands are functioning below reference standard levels. These impacts are expressed primarily by modification of supporting hydrology [Brooks et al., 2004]. Climate-induced hydrologic regime changes may additionally stress these systems, further decreasing their capacity to serve important ecotone functions. The condition of streams shows similar patterns; an in-depth stream assessment conducted through most of Pennsylvania by EPA using a systematic statistical sampling during 1993

and 1994 revealed that 27 percent of streams were in poor condition based on fish and insect populations (Mid-Atlantic Highlands Stream Assessment 2000).

8.3 Potential Climate Change Impacts to Pennsylvania Aquatic Ecosystems

While future scenarios related to climate change remain uncertain, the most significant effects predicted for stream and wetland communities are increased water temperature and increased hydrological variability, the latter of which may be reflected by changing seasonal patterns of water levels, reduced stream flows during dry periods, larger floods and longer droughts (Moore et al. 1997, Rogers and McCarty 2000). Some surface-water wetlands, which are believed to be the most vulnerable to these changes, may disappear completely. This loss of water to the system will stem mainly from greater runoff during severe storm events, longer drought periods, and increased evaporation and transpiration, rather than decreased precipitation (Moore et al. 1997). More severe storm events and extensive dry periods will create substantially altered flow patterns, essentially eliminating the flow pulse (below bankfull flood events) and resulting in major changes in channel morphology and aquatic habitat (Poff et al. 1996, Tockner et al. 2000, Amoros and Bornette 2002). In addition, water quality in streams is expected to decline due to increased flushing of contaminants from adjacent lands during run-off and production of higher sediment loads to downstream reaches through runoff and erosion of stream banks during more intense storm flows (Moore et al. 1997, Rogers and McCarty 2000).

Such changes in temperature, water quantity and water quality will most certainly affect stream and wetland biological communities. Climate change impacts across a number of natural systems at the global scale have shown significant range shifts averaging 6.1 km per decade towards the poles (Parmesan and Yohe, 2003); this includes fish. The largest negative impact may be in lost biodiversity (Fisher 2000, Tockner et al. 2000), the effects of which are exacerbated by human disturbance (Moore et al. 1997, Rogers and McCarty 2000). Habitat fragmentation from agriculture and urban development creates migration barriers that will prevent many species from moving to colder climates to offset warming temperature trends (Rogers and McCarty 2000). Although typically considered within terrestrial settings (e.g., forest patch sizes), fragmentation applies to aquatic habitats, as well. Hydrologic modification and stream-bank erosion isolate streams from their floodplains and nearby riparian wetlands, effectively reducing areas for flood refuge, larval development, and oviposition sites (Sedell et al. 1990, Tockner et al. 2000). This loss of hydrological connectivity not only reduces aquatic biodiversity, it also makes it more difficult for species to adapt to altered precipitation and temperature patterns. The predictability of timing and duration of high flow events has been shown to be important in determining the use of floodplain habitats by some fish species (Humphries et al., 1999).

Temperature is a critical component in aquatic systems, executing both physiological and behavioral influence on the survival and growth of nearly all macroinvertebrate and fish species (Sweeney et al. 1991, Ward 1992, Mountain 2002, Harper and Peckarsky 2006). For example, emergence of mayfly populations is initiated primarily by increases in water temperature (Sweeney et al. 1991, Watanabe et al. 1999, Harper and Peckarsky

2006). Consistently warmer temperatures earlier in the year can have negative impacts for the long-term health of mayfly populations, since early emergence coincides with reduced growth during the larval period, which reduces the size and fecundity of the adult mayfly (Peckarsky et al. 2001, Harper and Peckarsky 2006). Pennsylvania contains a vast multitude of headwater streams that provide high quality habitat for numerous coldwater species, including the brook trout (*Salvelinus fontinalis*) and the majority of intolerant mayfly, stonefly, and caddisfly species. Increased stream temperatures can negatively impact these organisms by exceeding their thermal tolerance levels, lowering dissolved oxygen concentrations, and biomagnifying toxins (Mountain 2002, Moore et al. 1997). Unlike intolerant species that typically cannot withstand high temperatures, many tolerant species respond to warmer temperatures through increased growth rates and fecundity (Sweeney et al. 1991). In addition, the general tolerance and opportunistic nature of these species will enable them to adjust to shorter and unpredictable hydroperiods. As a result, the commonwealth may see a decline in some of our most valued coldwater communities and a simultaneous increase in the abundance of less desirable biological assemblages, especially invasive species that outcompete and often decimate native populations (Rogers and McCarty 2000, Dukes and Mooney 1999).

Of special concern is the impact of higher temperatures and altered flow regimes on Eastern brook trout, not only because of its status as a recreationally and culturally important species, but because it is an indicator of high water quality and may be an early victim of deletrious impacts of climate change. A population status assessment of eastern brook trout was performed by the Eastern Brook Trout Joint Venture (Hudy et al., 2008; Hudy et al., 2005), and utilized known and predicted brook trout status to classify eastern U.S. subwatersheds according to the percentage of historical brook trout habitat that still maintained self-sustaining populations. The data for Pennsylvania (among all eastern U.S. states in the native range) identified 143 subwatersheds (10 percent) in which over 50 percent of brook trout habitat was intact; 550 subwatersheds (40 percent) in which less than 50 percent of brook trout habitat was intact; 612 subwatersheds (44 percent) from which self-sustaining populations were extirpated; and 72 subwatersheds (5 percent) where brook trout were absent but the explanation for the absence was unknown (i.e., either extirpation from or a lack of historical occurrence in those subwatersheds). Hudy et al, 2008 utilized this data to assess whether classification of subwatersheds could be reasonably well-predicted by utilizing the five factors of percent total forest, sulfate and nitrate deposition, percent mixed forest in the water corridor, percent agriculture, and road density; the classification was correct 71 percent of the time. The classification model was corroborated by a ranking of threats by resource managers; EBTJV (2006) interviewed regional fishery managers and asked them to rank perturbations and threats for all subwatersheds that historically supported reproducing brook trout populations, according to three categories of severity: (1) eliminates brook trout life cycle component; (2) reduces brook trout population; and (3) potentially impacts brook trout population. Across the entire study area of eastern U.S. states supporting brook trout, the top five perturbations listed as a category 1 or 2 severity for streams were high water temperature, agriculture, riparian condition, one or more non-native fish species, and urbanization; increased stream temperatures were ranked by biologists as the top threat to Appalachian brook trout (EBTJV 2006). Climate change will exacerbate all of these perturbations,

either alone or synergistically with continued land cover change. Increased stream temperature may be the first and most direct impact.

Increases in hydrological variability (larger floods and longer droughts) could have severe long-term effects on both stream and wetland communities (Harper and Peckarsky 2006, Humphries and Baldwin 2003). Larger peak flows will result in higher rates of sedimentation and increased scouring of stream banks and floodplains, both of which decrease survival and reproductive success for fish and macroinvertebrates (Chapman 1988, Fisher 2000). Fine sediment reduces stream insect and salmonid spawning habitats, and lowers survival rates of many insect species and salmonid embryos (Chapman 1988, Roy et al. 2003). Large flood events reduce survival rates for eggs laid alongside stream banks and floodprone areas and crush species lacking flood refugia (Karr and Chu 1999, Sedell et al. 1990). The greatest impacts will occur in urban areas with a high percentage of impervious surface where runoff is quickly routed to streams (Rogers and McCarty 2000). Furthermore, loss of seasonally predictable flood events and reduced groundwater recharge would affect many species that have adapted their life cycles to coincide with times of high water (Tockner et al. 2000, Amoros and Bornette 2002, Suen 2008). Climate change can negatively impact these populations in a multitude of ways, including mismatched timing of life cycle stages and aquatic habitat availability (e.g., aestivating eggs that rely on inundation to initiate hatching in seasonal wetlands), insufficient duration of inundation (e.g., aquatic life cycle stages dependent on longer hydroperiods), and lack of sufficient habitat refugia (e.g., young insect larvae and fish fry that depend on seasonal backwater areas to escape predation and ensure adequate food supply) (Poff and Ward 1989, Sedell et al. 1990, Firth and Fisher 1991, Sweeney et al. 1991, Bunn and Arthington 2002, Suen 2008). Hydrological factors are significant variables in structuring fish assemblages; alterations in the hydrology could greatly modify fish assemblage structure (Poff and Allan, 1995).

At a larger spatial scale, climate change is likely to alter the biogeochemistry of the Chesapeake watershed via the large contribution of the Susquehanna River to its total freshwater input (51 percent). The direction of change is not well constrained given the uncertainty in flow projections (Najar et al., 2008), as well as the lack of a mechanistic understanding of watershed processes. For example, two studies summarized in Najar et al. 2008 for the Susquehanna River Basin present estimates of percent change in annual streamflow of -4 to 24 percent. Nutrient and sediment loading during winter and spring will likely rise due to the anticipated increase in flow during this time, due to increased run-off and erosion of stream banks. In addition, large concentrations of nutrients (N and P) are stored by benthic biofilms (mostly algae) in the bed of streams through PA (Godwin et al. 2009). Once dislodged, this material is transported downstream (see Godwin and Carrick 2007; Godwin et al. 2009). Over a longer time frame, the impact of development and other land cover changes could control fluxes of both nitrogen and phosphorous by further altering both hydrology (through an increase in impervious surface) and nutrients and contaminants (contained in runoff).

8.4 A Case Study for Climate Change Impacts to Hydrology: Little Juniata Watershed

In order to provide context for the consideration of potential climate change impacts on aquatic ecosystems, we present a case study of a small mesoscale (845 km2) subwatershed in the Ridge and Valley physiographic province. While the reporting of general statewide estimates is informative, it is often impacts at the local scale that provide greater understanding of the issue. It is important to note that fine spatial scale assessment of potential impacts is generally lacking for aquatic resources, due to the enormous amount of complexity and site-specificity when predicting hydrologic change resulting from projected climate. Thus, we present this current research as a general example of the potential small-scale variability in effects, and not as a general example of future conditions state-wide.

The Little Juniata watershed is a subwatershed of the Juniata River, the second largest tributary to the Susquehanna River, which, in turn, is the largest tributary of Chesapeake Bay (McIlnay 2002). The Little Juniata watershed is located primarily within the Ridge and Valley physiographic province of central Pennsylvania, however, its headwaters are found in the Allegheny Front, the watershed divide and transitional region between the Ridge and Valley Province and the Allegheny Plateau. Most of the bedrock found in the watershed is sedimentary siliclastic and carbonate rock of alternating layers of sandstone, shale, and limestone. Valley floors can be either shale or limestone. The climate of the region is moderate, with an annual average temperature of 10 degrees C and monthly averages ranging from -3 degrees C in January to 22 degrees C in July. Average annual precipitation is 102 cm and is evenly distributed throughout the year, with substantial amounts of frozen precipitation in winter. It is representative of a Ridge and Valley subwatershed, and provides a relevant window into potential effects of climate change on headwater streams and wetlands.

Establishing the quantitative relationships among surface water, soil water, and groundwater conditions for dynamic climate scenarios, represents an essential step to understanding the problem of wetland dynamics. Topography, surficial geology, geomorphology, and the atmospheric state provide the geometrical, material, and forcing framework for simulating the effects of surface-groundwater interaction with wetlands. For this example, we applied a fully coupled and distributed modeling system which simulates surface water (overland, channel, lake), soil moisture, and groundwater dynamics. The model is referred to as the PIHM (Penn State Integrated Hydrologic Model; Qu and Duffy 2007). The model has shown dynamic interaction between groundwater level and evapotranspiration and local topographic and stream morphology effects on stream aquifer interactions. We constructed a simple future climate scenario by applying a daily temperature and precipitation change, obtained from monthly changes predicted by the model mean of the 21 GCMs under the A2 scenario.

Because of the high level of uncertainty associated with forecasting hydrologic variables with climate change in general and in the Mid-Atlantic in particular, it is important to focus on changes that could be ecologically relevant. Our approach is to use regional models of climate change and to feed the scenarios into an integrated, physically based hydrologic model and generate a range of possible conditions. The questions that we are

then investigating as ecologists are: what hydrological changes can we forecast with the most confidence, what potential and plausible hydrologic changes due to climate change could cause changes in the ability of wetlands and streams to provide ecologic services, and what can be done to prevent these plausible changes?

8.5 Ecologically-relevant Hydrologic Changes

8.5.1 Basin-Wide

Recharge: It appears that recharge stays the same in highlands and on the Alleghany front, increases in the major valleys, and is highly variable along stream corridors (Figure 8.2). The effect for wetlands depends on the location of the groundwater source (in highlands or closer to the streams), but if decreases in recharge adjacent to streams translates into drier conditions this could affect wetlands by generally reducing water levels and habitat complexity of the wetlands.

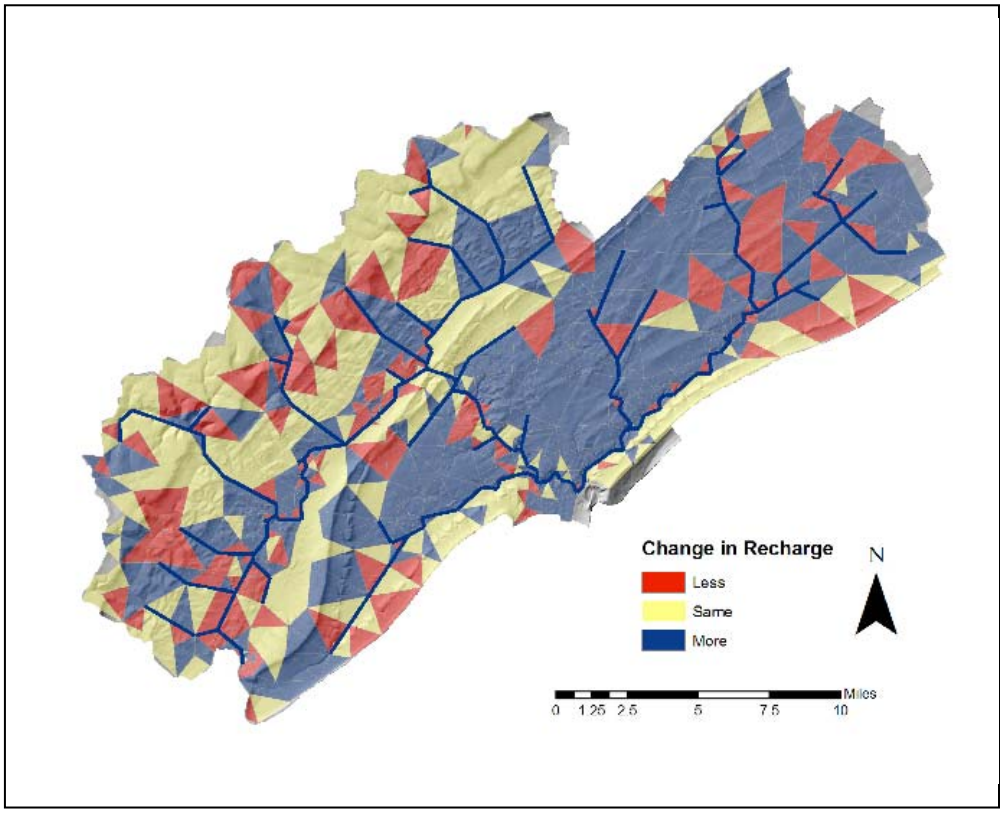


Figure 8.2. Change in recharge in the Little Juniata watershed under a scenario of climate change.

Water Table Depth: However, in the case of the study watershed, water table depths generally stay the same under forecasted conditions, with some rising of the water table in areas adjacent to streams throughout the watershed, and some lowering of the water

table near headwater streams in the valleys (Figure 8.3). Higher water tables near streams could result in wetter wetlands, with possible increases in groundwater driven microhabitats and an increase in plants that can tolerate wet conditions, which often tend to be non-invasive species. If lower water levels and drier conditions occur in the wetlands adjacent to headwaters in the valleys, this could result in a loss of ecological habitat complexity and an improvement of conditions favorable for invasive plant species.

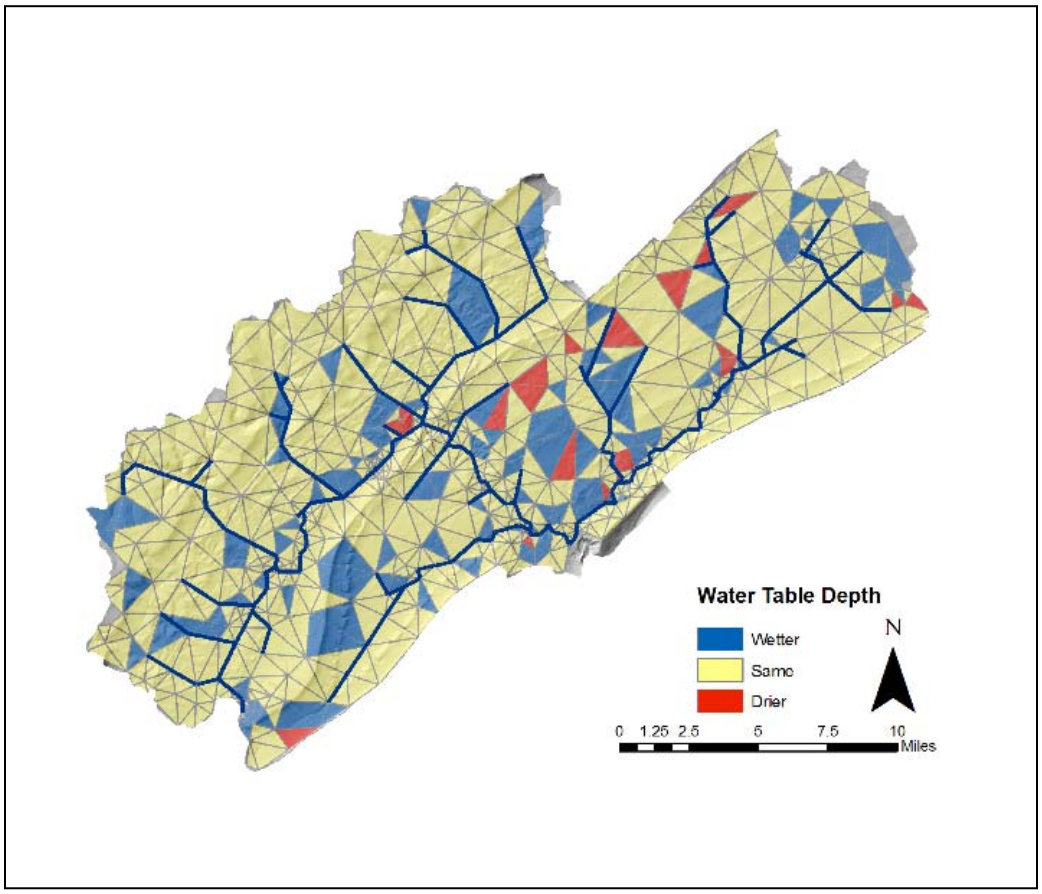


Figure 8.3. Change in water table depth in the Little Juniata watershed under a scenario of climate change.

8.5.2 In Stream

Gaining Streams: A gaining stream is a stream that is receiving groundwater from the water table. According to the model, on average for the year, most of the streams in the study watershed are gaining or receiving groundwater from the water table (Figure 8.4).

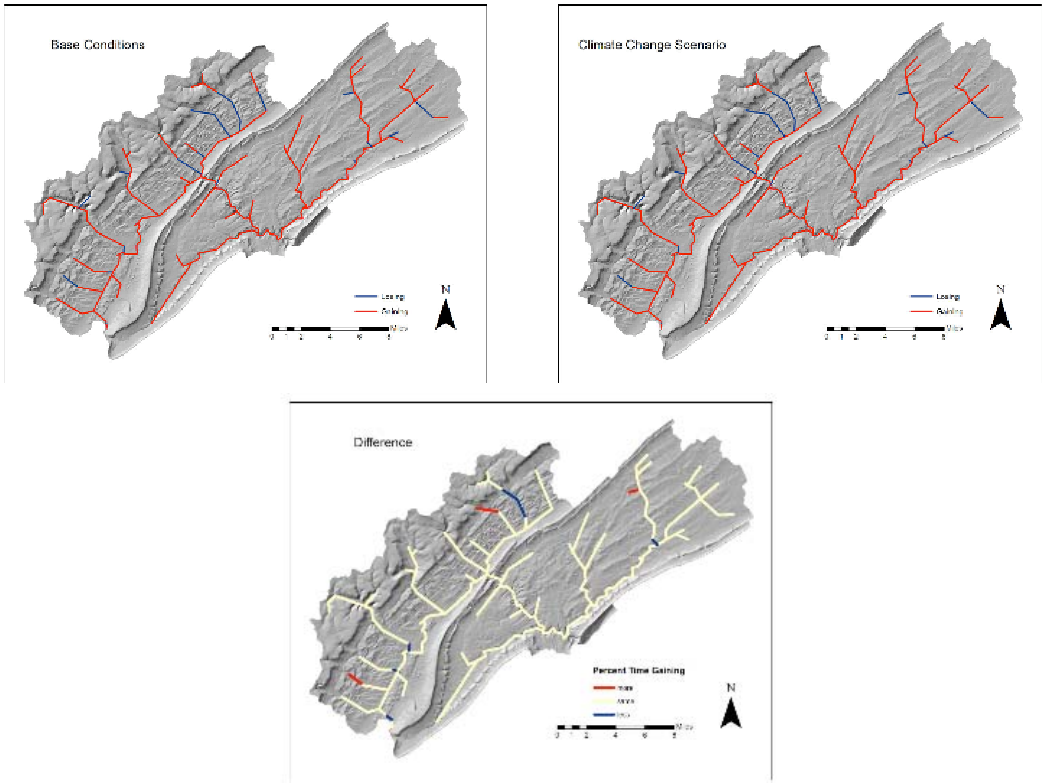


Figure 8.4. Change in gaining/losing streams in the Little Juniata watershed under a scenario of climate change.

There is little forecasted change in the proportion of distribution of streams that are gaining. This does not eliminate the possibility of important seasonal changes, however.

Stream Flow: Our analysis shows a nearly universal trend of an increase in discharge throughout the basin (Figure 8.5). An increase in stream flow translates into an increase in stream power, or the amount of work a stream can do in terms of moving materials. Under these conditions, increased erosion and deposition is likely to occur, especially in areas where stream banks are compromised with little vegetation to hold the soils in place. Increasing stream power can translate into increasing incision of streams and mean less of the small over bank flooding events, which are typically not highly detrimental to humans but very important in forming streamside habitats. Further, an increase in sediment deposition can cause a decrease in the rate of native plant species germination and can fill in troughs and hummocks within a wetland that act as important habitat.

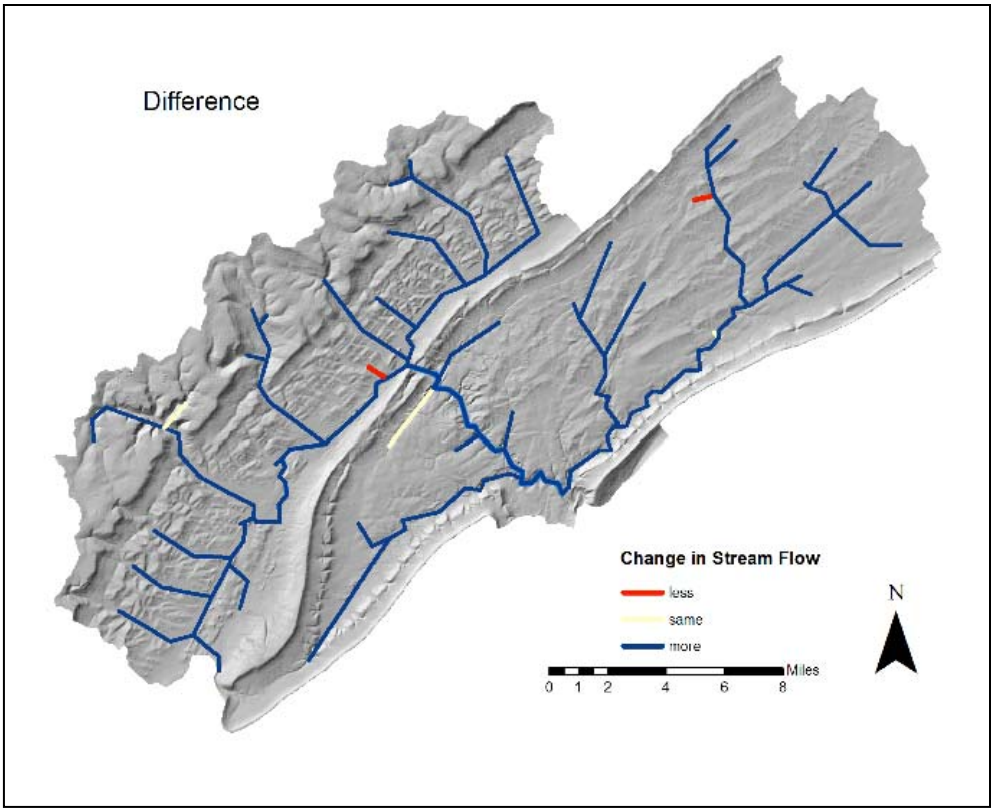


Figure 8.5. Change in stream flow in the Little Juniata watershed under a scenario of climate change.

8.5.3 Reach Scale

The majority of wetlands in Pennsylvania are associated with streams, and the large majority of those wetlands (by number) are associated with headwater conditions. In the information discussed above, some of the trends, such as a predicted increase in stream flow, occur throughout the watershed, while others vary throughout the landscape. The distribution and types of wetlands follow this model of high variability. When you walk along one of Pennsylvania's many small streams, you will encounter a variety and often a mix of aquatic ecosystem types including streams, floodplains, and wetlands. The distribution of these habitats is driven by a range of factors such as: topography or shape of the surrounding landscape, the underlying soils and geology, the frequency of which the area is flooded, and the level of direct (such as tile drainage) or indirect human disturbance (downcutting of streams). The effects of changes in hydrology will likely affect wetlands differently depending on both the physical characteristics in which the wetland is set and the type of human alteration in the landscape surrounding the wetland. Below are some illustrative examples of reaches or sections of stream in different landscape settings with some discussion of the possible impacts of projected hydrologic alterations under climate change.

Stream and Floodplain Dominated Reach in a Forested Setting: One reach in the watershed is moderately steep with a small perennial meandering stream, adjacent floodplain, and occasional wetland habitat. The floodplain is fairly disconnected from the stream meaning that it only receives water from the stream in relatively infrequent a flood events. The wetlands that occur in these systems typically occur in areas of groundwater discharge. For this particular reach, the floodplain habitats depend on the moderate-sized flooding events to provide stream flow for habitat formation and maintenance of water levels: in a sense these are the Goldilocks of floodplain habitats. They require flooding events that are not too large, but not too small. The wetland habitats, where there is saturated soil for the majority of the growing season, require a strong discharge of groundwater. As forecasted, the reach could potentially experience a 10 percent increase in stream flow, while the percent of time that it is a gaining stream would stay the same. One bank would show an increase in recharge and the other a decrease, and the reach as a whole would show a slight rise in the water table. In a forested watershed, where the riparian vegetative cover is maintained, stream banks are fairly stable and these forecasted changes may not have a large effect on the system.

Wetland Dominated Reach in an Agricultural Setting: Another reach in the watershed is a relatively wide and flat reach with a small, incised stream with many areas of wetlands dominated by groundwater discharge. This stream is in a highly agricultural setting where little riparian vegetation is still intact. The stream is forecasted to experience a 16 percent increase in stream flow, see little change as a gaining stream, experience an increase in recharge from both banks, and show a slight rise in the annual average water table. In this scenario, a wetter system may help to maintain the groundwater-dependent habitat types that still exist, however the increase in stream flow could increase sedimentation both in the reach and downstream, depending on management practices on the farm and in the rest of the stream's watershed. Depending on the size and timing of the increased flow, this could increase the extent that the stream is incised and decrease the connection between the stream and the wetland, despite a general trend toward a rising water table. An increase in runoff could cause an increase in standing water in the system, altering the physical structure of the habitat

8.6 Summary of Impacts

- The most significant climate change effects predicted for stream and wetland communities are increased water temperature and increased hydrological variability (high agreement, much evidence; high confidence).
- Pennsylvania may see a decline in some of our most valued coldwater communities and a simultaneous increase in the abundance of less desirable biological assemblages, especially invasive species. Eastern Brook Trout will continue to decline as a result of higher water temperatures (high agreement, much evidence; high confidence).
- Wetlands may experience a similar change in habitat conditions, as hydrologic variability changes habitat structure (high agreement, limited evidence). Potential impacts on other ecosystem services cannot be predicted at this time.

- Wetlands and headwater streams in Pennsylvania are already compromised in their ability to provide ecosystem services, due to degraded conditions resulting from modification of hydrology and nutrient enrichment (high agreement, much evidence; very high confidence). These stressors primarily arise from human activities associated with agriculture and development.
- Impacts of climate change on aquatic ecosystems will be difficult to detect because of the continuation of primary stressors to their condition such as development and invasive species (high agreement, much evidence; high confidence).
- Ecologically-relevant hydrologic responses to precipitation and temperature will vary over the spatial scale of a small watershed (limited evidence and study; no estimate of consensus available).
- Although the complexity and interconnectedness of aquatic ecosystems makes it difficult to predict specific impacts on particular species and ecosystem functioning, it is this same complexity and connectivity that may lend some resiliency to ecosystems in the face of environmental change (low agreement, limited evidence).

8.7 Potential Adaptations

Strategies to avoid the above impacts from climate change need to center around maintaining and improving the resiliency of aquatic systems through minimization of increased stream temperature, nutrient enrichment, hydrologic modification, habitat fragmentation and degradation, and species loss. Such actions would include:

- Protection of existing stream and wetland habitat, especially intact habitat for identified species of interest, such as Eastern brook trout (EBTJV 2008).
- Consideration of hydrological connectivity within and between stream and wetland habitats.
- Maintenance of riparian forests for moderation of stream temperature and treatment of run-off from adjoining lands.
- Implementation of Best Management Practices to reduce nutrient loading.
- Restoration of aquatic ecosystems such as streams and wetlands wherever possible.
- Minimize groundwater pumping for irrigation, human consumption, etc., that removes water from aquatic and wetland ecosystems.

8.8 Informational needs for Aquatic Ecosystems

- What are the projected increases in temperature in streams of the commonwealth, especially in coldwater habitats?
- What is the projected change in flow rates and hydroperiods in watersheds across the commonwealth?
- What controls the retention of nutrients versus their export to aquatic systems once they are deposited onto the landscape?

- What is the existing condition of streams, lakes, and wetlands across the commonwealth, how will that affect their ability to respond to additional climate change impacts, and how will that affect the production of ecosystem services?
- How will humans continue to interact with aquatic ecosystems under scenarios of climate change, e.g., how will changing patterns of water resource use affect wetlands and streams?

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9.0 Agriculture

Agriculture in Pennsylvania, like agriculture in the rest of the United States and worldwide, has an intrinsic relationship with climate. Most crop and livestock production in Pennsylvania occurs partly or entirely in the open air, exposed to the elements and dependent on the weather for success. Even production that occurs under controlled climatic conditions, such as a mushroom house, is affected by climate through heating and cooling costs.

9.1 Present-Day Pennsylvania Agriculture[2]

According to the *2007 Census of Agriculture*, there are approximately 63,000 farms in Pennsylvania. These farms have a total of about 7.8 million acres of land, of which 4.9 million acres are cropland. Agricultural land constitutes about 27 percent of all land in Pennsylvania, making agriculture the second-largest land use in Pennsylvania after forests. Most farms in Pennsylvania are small relative to farming operations often seen in the Midwest and Great Plains. About 41 percent of all Pennsylvania farms have 49 or fewer acres and another 41 percent have 50 to 179 acres. Only 1 percent of Pennsylvania farms have 1,000 acres or more, and only about 3 percent have 500 to 999 acres.

Breaking farms down by farm revenue (market value of agricultural products sold plus government payments) also reveals a preponderance of small farms. More than one-fourth (28 percent) of Pennsylvania farms had less than $1,000 in farm revenue in 2007, and about one-third (32 percent) had between $1,000 and $9,999 in farm revenue. This breakdown also reveals that the farms with the highest revenue per farm accounted for much of Pennsylvania's total farm revenue of $5.9 billion in 2007. Farms with revenue of $5 million or more constituted only 0.1 percent of all Pennsylvania farms but accounted for about one-seventh (15 percent) of total Pennsylvania farm revenue. Farms with revenue between $1 million and $5 million constituted 1.4 percent of all Pennsylvania farms but accounted for more than one-fourth (27 percent) of total Pennsylvania farm revenue. Figures 9.1 and 9.2 display the breakdown of the number of farms in Pennsylvania by revenue category and the contribution of each to total revenue, respectively.

[2] The statistics in this section are drawn from the *2007 Census of Agriculture* except where noted.

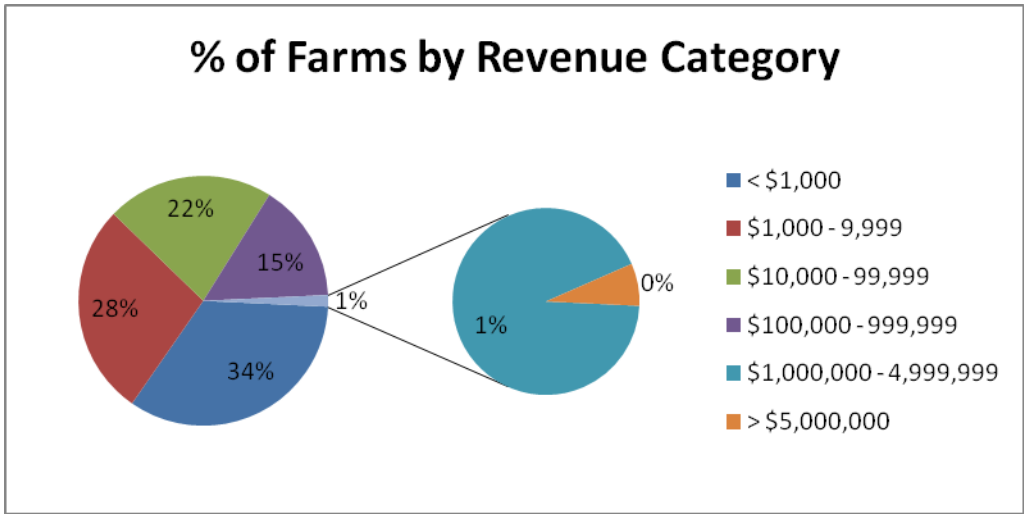

Figure 9.1. Percentage of Pennsylvania Farms by Revenue Category

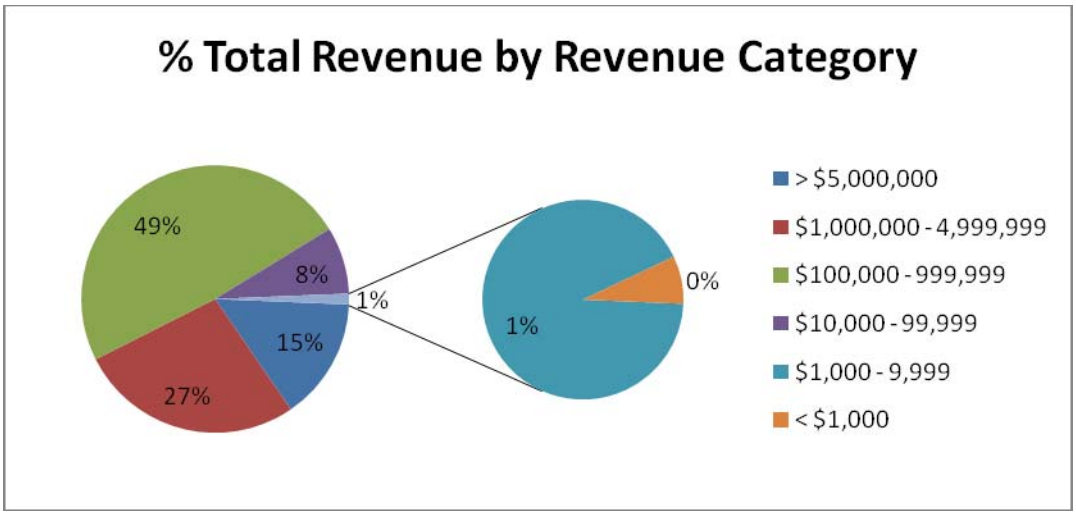

Figure 9.2. Percentage of Total Revenue of Pennsylvania Farms by Revenue Category

The 2007 *Census of Agriculture* also categorizes farms according to a typology developed by the Economic Research Service at the U.S. Department of Agriculture (Hoppe, Perry and Banker 2000). The typology has eight categories: limited resource farms, retirement farms, residential/lifestyle farms, farming occupation/lower sales, farming occupation/higher sales, large family farms, very large family farms, and nonfamily farms.[3] By this typology, the three largest categories in terms of number of

[3] A limited resource farm is any small farm (sales less than $250,000) with gross sales less than $100,000, total farm assets less than $150,000, and total operator household income less than $20,000. Retirement farms are small farms whose operators report that they are retired. Residential/lifestyle farms are small

farms are residential/lifestyle farms (36 percent), retirement farms (19 percent), and limited resource farms (16 percent).

Livestock and poultry accounted for about two-thirds (68 percent) of total agricultural product sales in 2007 while crops accounted for about one-third (32 percent). The single-largest sales category across all crops and livestock was dairy products, accounting for about one-third (33 percent) of total agricultural product sales. After dairy comes poultry and eggs at about one-sixth (17 percent), cattle and calves at 10 percent, mushrooms at 8 percent, other nursery and greenhouse products (aside from mushrooms) at 7 percent, hogs and pigs at 6 percent, and corn at 6 percent.[4] These seven product categories when taken together account for the vast majority (86 percent) of total agricultural product sales in Pennsylvania.[5] The remaining sales are divided among a diverse set of crops and livestock, including soybeans, fruits, tree nuts, berries, vegetables, melons, potatoes, wheat, oats, barley, tobacco, Christmas trees, horses, and aquaculture products. Figure 9.3 illustrates the breakdown of agricultural sales by product.

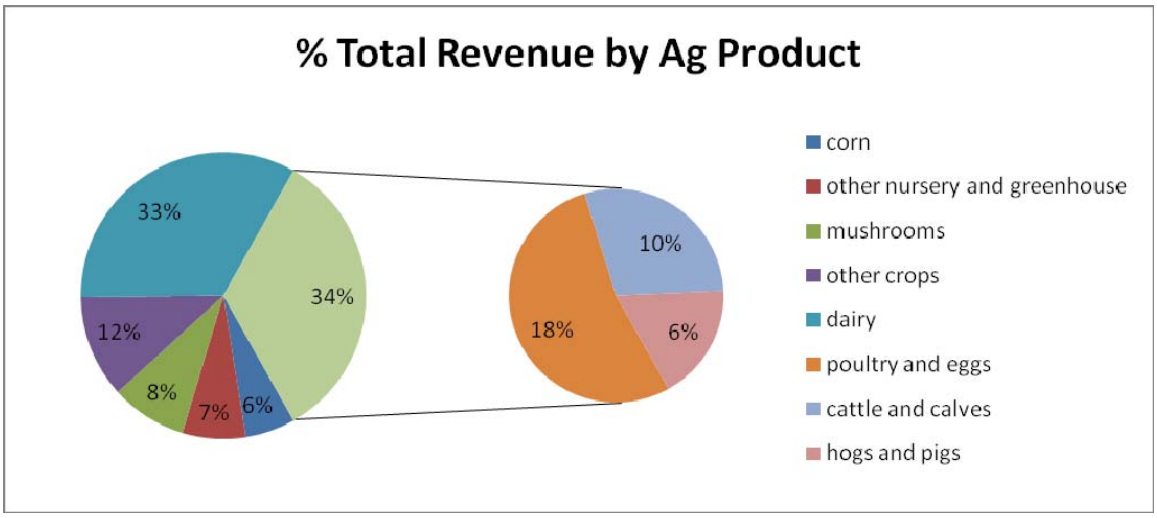

Figure 9.3. Percentage of Agricultural Sales by Product

About half (51 percent) of Pennsylvania's fruit and tree nut acreage was devoted to apples, about one-third (31 percent) to grapes, and about one-ninth (11 percent) to

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farms whose operators report a major occupation other than farming, excluding limited resource farms. Farming occupation/lower-sales refers to small farms with sales less than $100,000 whose operators report farming as their major occupation, excluding limited resource farms. Farming occupation/higher-sales refers to small farms with sales between $100,000 and $249,999 whose operators report farming as their major occupation. Large family farms are those with sales between $250,000 and $499,999, while very large family farms are those with sales of $500,000 or more. Nonfamily farms are those organized as nonfamily corporations or cooperatives, as well as farms operated by hired managers.

[4] Other nursery and greenhouse products, aside from mushrooms, that are important in Pennsylvania include bedding/garden plants, nursery stock, potted plants, greenhouse tomatoes, and cut flowers.

[5] The percentages reported for each of the six product categories add up to 87 percent, which is different from 86 percent due to rounding.

peaches. About one-third (31 percent) of Pennsylvania's vegetable, melon and potato acreage was devoted to sweet corn, about one-sixth (17 percent) to potatoes, and about one-sixth (17 percent) to snap beans.

Of Pennsylvania's 4.9 million acres of cropland in 2007, 3.9 million were harvested. The acreage not harvested was mainly held idle that year or used as pasture. Only about 1 percent of all cropland was not harvested in 2007 because of crop failures.

Of the 3.9 million harvested acres, a little less than one-half (44 percent) were hay. One-fourth (25 percent) were corn harvested for grain, and about one-ninth (11 percent) were corn harvested as silage. Another one-ninth (11 percent) were soybeans. These four product categories when taken together account for the vast majority (91 percent) of total harvested acreage. The remaining harvested acreage is divided among a wide range of other crops. Pennsylvania currently produces some small grains (wheat, barley, oats and rye), but they are a small proportion (7 percent) of harvested acreage. The single largest small grain is wheat, at 4 percent of harvested acreage. Corn for grain and soybeans account for a higher percentage of harvested acreage (36 percent) than agricultural product sales (8 percent) or crop sales (24 percent) because much corn and soybeans in Pennsylvania is used on the farm to feed livestock instead of being sold.

Lancaster County accounts for nearly one-fifth (18 percent) of total agricultural product sales in Pennsylvania. Of Pennsylvania's 67 counties, 11 in the southeast (Adams, Berks, Chester, Cumberland, Dauphin, Franklin, Lancaster, Lebanon, Perry, Schuylkill, and York) account for more than half (59 percent) of total Pennsylvania agricultural product sales. Lancaster County is well-known for its dairy farms but it is also an important producer of other commodities. Lancaster County has one-fifth (20 percent) of the state's dairy product sales, nearly one-third (31 percent) of the state's sales of hogs and pigs, nearly one-third (30 percent) for poultry and eggs, and more than one-fifth (22 percent) for cattle and calves. After Lancaster County comes Chester County (10 percent of Pennsylvania's total agricultural sales). Chester County accounts for over two-thirds (71 percent) of the state's mushroom sales.

While Pennsylvania agriculture is regionally diverse, one common theme is the importance of dairy and cattle production across all regions of the state. In the northwest, southwest and south-central parts of the state, major products in terms of sales include dairy, cattle and calves, and nursery and greenhouse crops. In the north central and northeast parts of the state, major products include dairy, cattle and calves, and hogs and pigs. In central Pennsylvania, major products include dairy, poultry and eggs, hogs and pigs, and cattle and calves. In the southeast part of the state, as noted above, major products include dairy, poultry and eggs, hogs and pigs, and cattle and calves.

Irrigation is uncommon in present-day Pennsylvania agriculture. Irrigated land in 2007 was approximately 38,000 acres, less than 1 percent of the total 4.9 million acres of cropland. Although Pennsylvania certainly has droughts, and some droughts are severe, there is adequate precipitation in most years for field crop production. The single-largest agricultural product category in terms of irrigated acreage is vegetables (41 percent of all

irrigated acreage), followed by orchards (10 percent). Approximately 38 percent of total berry acreage and 29 percent of total vegetable acreage are irrigated.

About 1 percent of Pennsylvania farms are organic farms, either partly organic (some organic sales and some non-organic sales) or wholly organic. Organic product sales accounted for about 1 percent of total Pennsylvania agricultural product sales in 2007. About 45,000 acres were in organic production in 2007, with another 14,000 acres in the process of being converted to organic. As part of USDA's organic certification process, a period of at least 3 years must pass during which time all organic standards are followed on a parcel of land before crops or livestock products from that land may be labeled and marketed as organic.

About 233,000 acres, or 5 percent of all Pennsylvania cropland, is enrolled in government conservation programs such as the Conservation Reserve Program (CRP), Conservation Reserve Enhancement Program (CREP), and Wetlands Reserve Program. This is about one-half the percentage for U.S. cropland as a whole. All three are voluntary programs under which the U.S. Department of Agriculture contracts with farmers and landowners to retire agricultural land from production. CRP and CREP are directed at highly erodible and environmentally sensitive agricultural land, with land retirements running from 10 to 15 years. Land enrolled in CRP and CREP must be planted with grasses, trees, and other cover crops. WRP is directed at restoration and protection of wetlands, and uses three enrollment schemes: permanent easements, 30-year easements, and 10-year cost-share agreements.

Nearly one-fourth (23 percent) of Pennsylvania cropland was enrolled in crop insurance programs in 2007. The crops with the highest percentage of acreage insured in 2007 were grapes (82 percent) and apples (67 percent) (USDA, Risk Management Agency 2008). The 2008 Farm Bill offers several types of crop yield and revenue insurance. Crop yield insurance programs include insurance against losses due natural causes such as drought, excessive moisture, hail, wind, frost, insects, and disease; catastrophic loss insurance; and a group risk plan that uses county yields instead of farm yields as the basis for determining whether there was a loss. Revenue insurance programs include gross revenue coverage that insures against gross revenue falling below a specified level; group risk income protection that uses county yields instead of farm yields; and adjusted gross revenue insurance that insures the revenue of an entire farm rather than a specific crop.

9.2 Economic and Policy Scenarios

Agriculture in Pennsylvania has changed dramatically since 1900 and will likely change in profound ways between now and 2100 regardless of whether climate change is large or small. This section outlines some of the major forces in addition to climate change that may impact Pennsylvania agriculture in coming years and decades.

9.2.1 Supply

Pennsylvania agriculture, like U.S. agriculture as a whole, has changed radically during the last century. With the notable exception of the Amish, tractors and other farm machinery have virtually eliminated the use of draft animals and have made it possible for a single farmer to cultivate tracts of land orders of magnitude larger than a century ago. The introduction of synthetic organic pesticides in the 1940s revolutionized the control of weeds and insects. Similarly, there has been tremendous growth in the use of manufactured fertilizers and hybrid seeds. Farmers have become highly specialized in the livestock products and crops they produce, and they have become much more dependent on purchased inputs. Crops that were virtually unheard of 100 years ago, such as soybeans, are of major importance today. As agricultural productivity has risen, and as real (inflation-adjusted) prices of farm commodities have fallen, substantial acreage in Pennsylvania has been taken out of agriculture and either returned to forest or converted to urban uses.

There are few reasons to expect this rapid pace of technical change in U.S. and Pennsylvania agriculture to slow down during the rest of this century. The basic science of biotechnology is progressing very rapidly, and genetically engineered (GE) crops have made significant market penetration in the U.S. for corn, soybeans and cotton (Fernandez-Cornejo and Caswell 2006). Figures 9.4 and 9.5 show improvements in agricultural productivity over time and percent annual growth in agricultural productivity by state, respectively. These figures are included to display the ability of U.S. and Pennsylvania agricultural to translate rapid technological improvement into productivity gains.

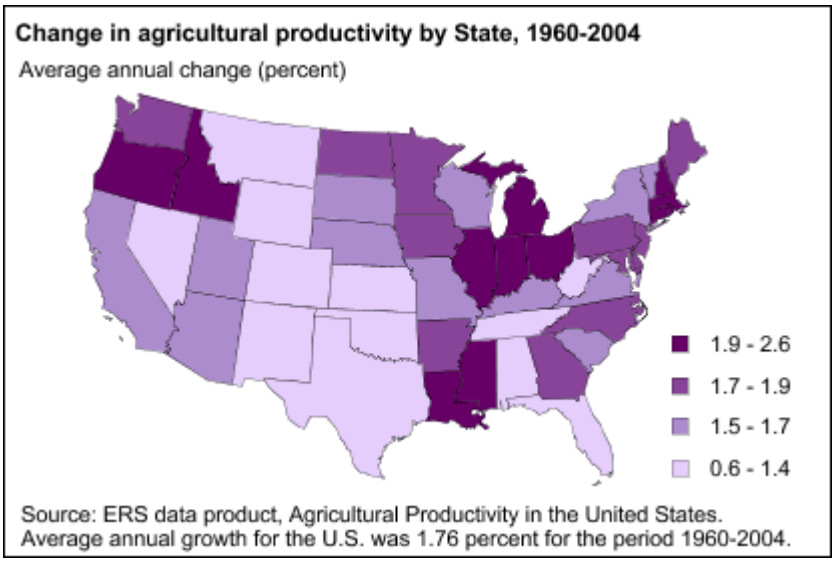


Figure 9.4. Annual Percent Change in Agricultural Productivity by State

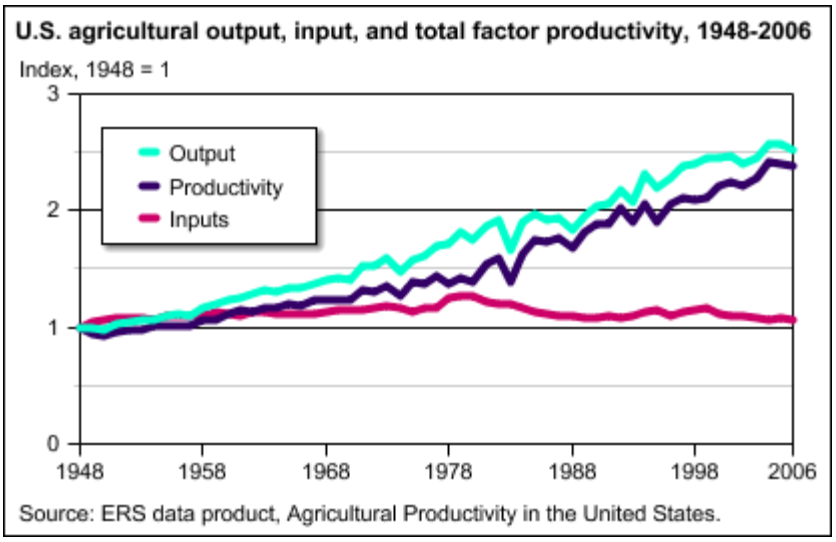


Figure 9.5. U.S. Agricultural Productivity 1948-2006

The two principal GE technologies currently being used are herbicide-tolerant varieties, that allow crops to survive certain herbicides that previously would have killed them along with the weeds, and insect-resistant varieties, that contain a gene that produces a protein toxic to certain insects. Some GE crops have both traits. Published state-level statistics on GE adoption rates for crops do not break out Pennsylvania from an "other states" category, but in 2008 for the U.S. as a whole 80 percent of all corn acreage and 92 percent of all soybean acreage were planted with GE varieties (USDA, National Agricultural Statistics Service, 2008a).

GE technologies under development include viral/fungal resistance; resistance to cold, drought, frost, and salinity; more efficient use of nitrogen; increased yields; and improved nutritional characteristics and product quality (Fernandez-Cornejo and Caswell 2006). Most of the GE technologies developed and adopted to date have been for corn, soybeans and cotton, but R&D is underway to extend GE technologies to other crops.

Animal biotechnology has attracted significant public scrutiny because of cloning but there are other possibilities, such as livestock that process feed more efficiently, leading to reduced feeding requirements and fewer nutrients in animal wastes. Feed may also be genetically modified so as to reduce nutrients in livestock wastes. GE vaccines and drugs could reduce livestock mortality and increase yields (Abler and Shortle 2000).

GE technologies have been criticized on various grounds, including concerns about food safety, environmental side-effects, animal welfare, and who benefits (seed companies versus farmers, farmers versus consumers, and rich countries versus poor countries). It is unclear at this time whether these concerns will translate into regulations that significantly slow the development and adoption of GE technologies in U.S. agriculture. The four IPCC scenarios outlined earlier in this report have different rates of technical change, with the most rapid technical change in scenarios A1 and B1 and the least rapid in scenarios A2 and B2.

In addition to genetic engineering, precision agriculture has the potential to significantly increase agricultural productivity (McBratney et al. 2005). Precision agriculture gives farmers much greater control over microclimates and within-field variations in soil conditions, nutrients, and pest populations. It uses remote sensing, wireless sensing, and information technology to achieve very precise control over agricultural input applications (chemicals, fertilizers, seeds, etc.) at the field level. This may be accompanied by computer-based decision support systems to aid farmers with production decision-making. The environment can benefit insofar as precision agriculture permits fertilizers and pesticides to be applied more precisely where they are needed at the times of the year when they are needed.

Future improvements in modeling smaller scale climatic processes such as thunderstorms can be expected to lead to improved weather forecasts. Improved forecasts may lead farmers to make better choices about what crops to plant, when to plant and harvest, when to protect temperature-sensitive crops such as tree fruits, when to fertilize, and other farm management decisions (Abler and Shortle 2000). This can be expected to increase agricultural productivity.

The future production potential of Pennsylvania agriculture will depend not only on productivity growth but also on the availability of farmland. One factor that has led to a decline in farmland in many areas is conversion of agricultural land to urban uses such as housing, retail, and office space. This conversion, in turn, has been driven by suburban population growth. Projections by the U.S. Census Bureau (2005) show Pennsylvania's total population rising only about 4 percent between 2000 and 2030, compared to about 29 percent for the U.S. as a whole. Projections by the Pennsylvania State Data Center (2008) suggest a somewhat higher population growth of about 7 percent for the state between 2000 and 2030.

At the county level, the Pennsylvania State Data Center (2008) projections indicate continued strong population growth in the southeastern Pennsylvania, with population losses in western and northern Pennsylvania. As noted above, agriculture in Pennsylvania is currently concentrated in the southeast part of the state. Lancaster County, which currently accounts for nearly one-fifth (18 percent) of total agricultural product sales in Pennsylvania, is projected to see its population increase by about 18 percent between 2000 and 2030. The population of neighboring Chester County, which currently accounts for 10 percent of Pennsylvania's agricultural product sales, is projected to rise by almost 60 percent. Figure 9.6 displays projected trends in population change by county to 2030. Compounding the effects of population growth may be future growth in real household income, which may manifest itself in larger homes and lot sizes, and thus more residential land use, a tendency evident over the last 30 to 40 years (Abler and Shortle 2000). We can conclude that there will continue to be strong pressures in southeastern Pennsylvania to convert agricultural land to urban uses. One moderating influence on these pressures will be Pennsylvania's Farmland Preservation program, which has preserved over 400,000 acres of farmland to date solely for agricultural use.

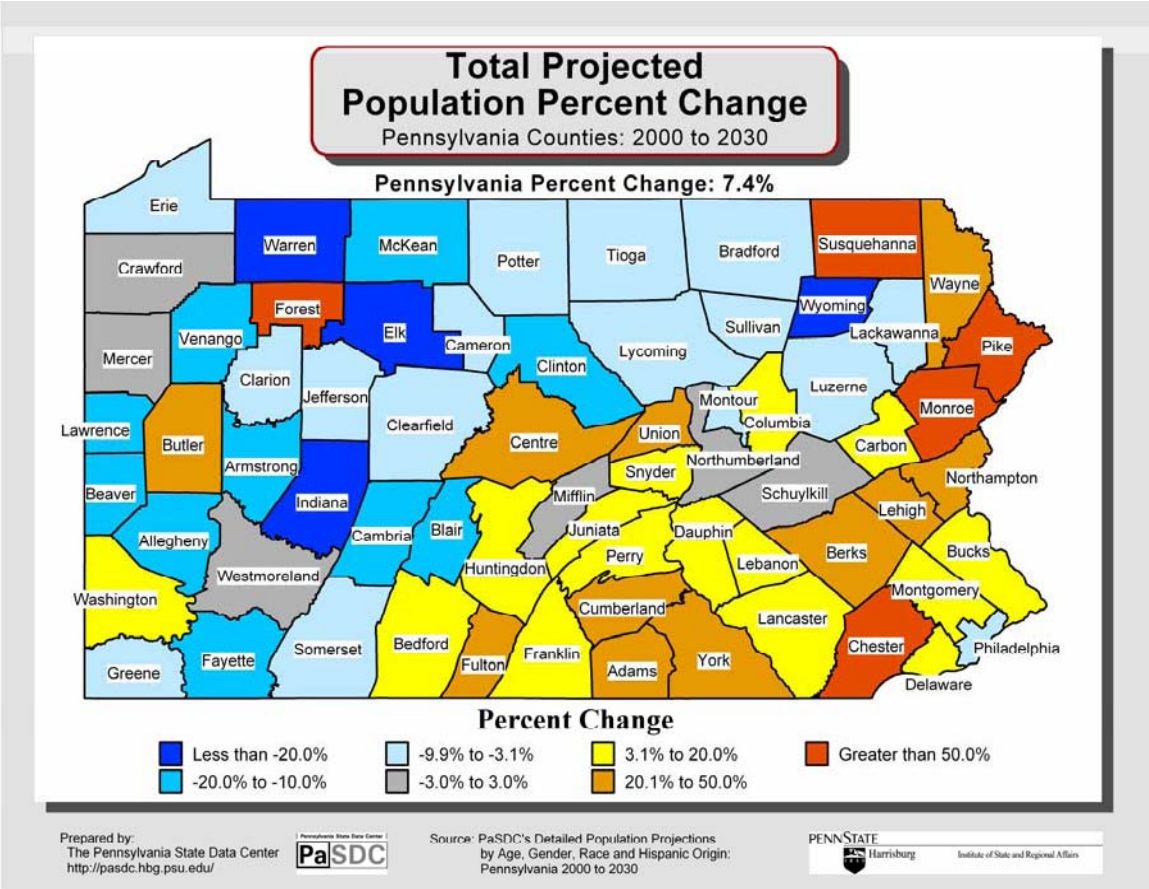


Figure 9.6. Projected Pennsylvania Population Change by County to 2030

For these reasons, there may be less crop and livestock acreage in southeastern Pennsylvania in the future than there is today. At the same time, crop and livestock yields on the remaining acreage will likely be significantly higher than they are today. There may be some growth in the number of residential/lifestyle farms in Pennsylvania, as people move to the countryside to take advantage of rural amenities (Abler and Shortle 2000). Whether these residential/lifestyle farms will represent a net addition to the number of farms or simply a conversion from other types of farms is unclear.

Another trend that may affect Pennsylvania crop and livestock production in coming decades is environmental regulation, particularly with regard to the Chesapeake Bay. The Chesapeake Bay is one of the most valuable natural resources in the United States, but human activity within the Chesapeake Bay watershed has had serious impacts on this ecologically rich area. Soil erosion and nutrient runoff from crop and livestock production have played major roles in the decline of water quality in the Bay (Abler et al. 2002). The Chesapeake Bay watershed includes Lancaster County and several other Pennsylvania counties in the southeast and central parts of the state with significant agricultural production. Figure 9.7 displays the Bay watershed in Pennsylvania overlaid

with county detail. More stringent environmental regulations on farms in the Chesapeake Bay watershed may be imposed in coming decades, and farms in other watersheds may also face additional regulations.

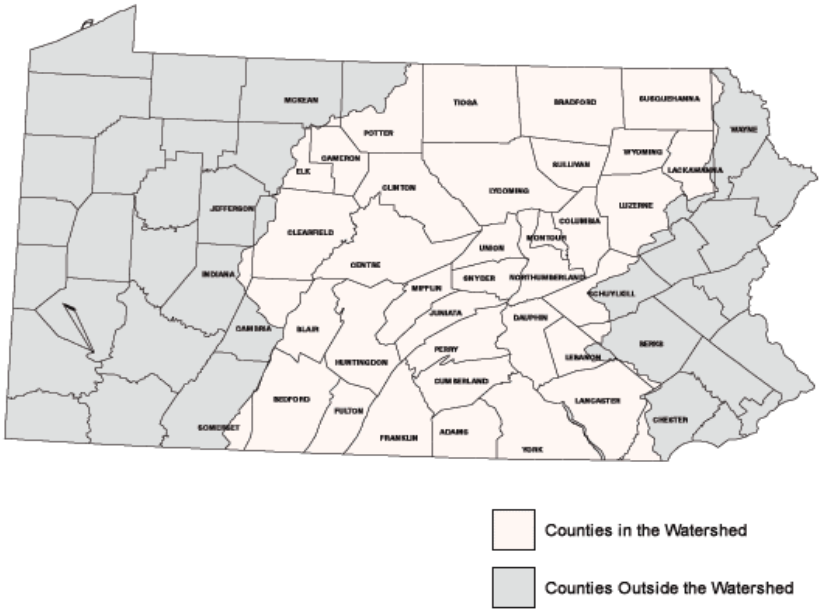


Figure 9.7. Chesapeake Bay Watershed in Pennsylvania with County Detail (Chesapeake Bay Foundation 2009)

9.2.2 Demand and Global Markets

Pennsylvania is part of local, regional, national, and global markets for food and agricultural products. In some cases, such as hay and certain seasonal fruits and vegetables, prices are determined on local and regional markets. Changes in demand or supply within Pennsylvania will affect prices facing farmers, consumers and others in the supply chain. In other cases, such as dairy products and mushrooms, prices are determined on national and global markets but Pennsylvania is a large enough producer of these products that changes in supply within the state will have a noticeable impact on markets. In still other cases, such as corn as soybeans, prices are determined on global markets, and Pennsylvania has such as small share of the global market that what happens within the state has no significant impact on market prices.

One important trend in recent years has been growing demand for organic products. Organic product sales rose from less than $4 billion in 1997 to nearly $18 billion in 2007, and now account for about 2.5 percent of total U.S. food sales (USDA, Economic Research Service 2007). Fresh fruits and vegetables account for over one-third (39 percent) of organic product sales, followed by dairy (15 percent) and beverages (14 percent). The current recession has halted the trend toward organic products, but it will probably resume after the economy recovers. Pennsylvania farmers can be expected to respond to this trend by expanding their production of organic products. The result of

this trend combined with technological change through biotechnology could be a split in Pennsylvania agriculture into two production systems: one heavily invested in biotechnology, and one organic.

Another trend that is becoming important is growing demand for local foods—foods produced within the consumer's county or state, depending on the definition of "local." The reasons why some consumers prefer local foods include freshness, supporting local farmers, developing personal relationships with food producers, and concerns about the environmental impacts (such as greenhouse gas emissions) of transporting food long distances (Zepeda and Leviten-Reid 2004). There are few reliable statistics on market shares of local foods. To the extent that this trend continues there will be a growing demand by Pennsylvania consumers for Pennsylvania food and agricultural products, particularly fresh fruits and vegetables.

Demand for fish and seafood products is growing worldwide even as the catch from many wild fisheries has fallen off significantly during the past two decades and some fisheries have collapsed entirely. The aquaculture industry has arisen to fill this void, and most of the net growth in global fish production in recent years has come from the development of aquaculture (Delgado et al. 2003). If these trends continue we can expect a growing demand for Pennsylvania aquaculture products.

Projections of world market prices for agricultural commodities in coming decades depend on the assumptions made about global demand relative to global supply. Demand will be growing due to global population growth, growing per capita incomes (especially in developing countries such as China and India), and possibly increasing demand for biofuels. Supply will be growing primarily due to increases in crop and livestock yields but also, in some countries such as Brazil, growth in acreage. The four IPCC scenarios used in this report differ in regard to their assumptions about population growth and economic growth. The A1 and B1 scenarios are characterized by high rates of economic growth, with population growth increasing until mid-century and declining afterwards. In the A2 scenario, population growth rates continuously increase throughout the century while economic growth is mixed. Scenario B2 is similar to A2, except that population grows more slowly in B2.

Projections of world market prices also depend on the assumptions made about international trade and trade agreements. While there has been a substantial reduction in import tariffs worldwide for industrial products during the last six decades, barriers to food and agricultural trade have been reduced much more slowly and in many cases have increased. Dairy products are among the agricultural products still facing very high import tariffs in many countries, including Canada, the European Union, India, Japan, South Korea, and the United States. If future global trade agreements lower these tariffs, dairy producers in Pennsylvania will face greater competition from low-cost producers in New Zealand, Australia, and Argentina (Langley, Somwaru, and Normile 2006). The four IPCC scenarios differ in regard to their assumptions about international trade agreements. The A1 and B1 scenarios assume greater global integration and

convergence, while scenario A2 assumes a heterogeneous world and scenario B2 assumes a decline in the importance of international institutions.

In the near term, the USDA's agricultural baseline projections for 2009-2018 indicate that growing global demand for agricultural products, combined with ethanol demand for corn in the U.S. and biodiesel demand for vegetable oils in the European Union, will cause prices for corn, oilseeds, and many other crops to remain well above their historical levels (USDA, Economic Research Service 2009a). At the same time, these projections do not indicate a return to the record high agricultural prices seen in the first half of 2008. The projections show U.S. retail food prices increasing more than the general inflation rate during 2009-2011, but after that returning to the longer term relationship of rising less than the general inflation rate.

Global markets for agricultural commodities are becoming more tightly linked with global energy markets due to biofuels. If oil prices are high enough to make biofuels profitable, then prices of energy crops such as corn become directly linked to the price of oil because those crops can always be turned into biofuels that compete with petroleum-based fuels. This means that projections of world markets for agricultural commodities must take into account projections for energy markets, and vice versa. Projections of world oil prices to 2030 by the Energy Information Administration (EIA) (2008) for their "reference case" show the price of oil hovering around $70 per barrel in inflation-adjusted 2006 dollars during 2015-2030. The EIA also has "high" and "low" projections, with the projected 2030 price of oil in the high case about 65 percent greater than the reference case, and the projected 2030 price in the low case about 40 percent less than the reference case.

Hardly any crops in Pennsylvania are currently used as energy crops—to produce liquid fuels, or heat or electricity via direct combustion. Energy crops could potentially become important in the future depending on global energy markets; on scientific progress in developing crops and crop processing technologies that significantly reduce the cost of deriving energy from these crops; and on government energy and agricultural policies. Aside from corn, possibilities for producing ethanol include switchgrass, cool season grasses, winter barley, and sugar beets. Possibilities for producing biodiesel include soybeans and canola. Switchgrass, cool season grasses, winter wheat, and corn stover are candidates for energy production via direct combustion (Roth 2007).

9.3 Climate Change Impacts

The climate projections in Section 4 of this report indicate that annual mean summer temperatures in Pennsylvania may increase on the order of 2-2.5 degrees C during 2046-2065 and 2.5-4.5 degrees C during 2080-2099, depending on the climate scenario, with annual mean winter temperatures increasing somewhat less—around 1.5-2 degrees C during 2046-2065 and 2-3 degrees C during 2080-2099. Most of the climate models project increases in average precipitation in Pennsylvania, with the average summer increase across all models on the order of 0-5 percent during 2046-2065 and a little more than that during 2080-2099. Winter precipitation is projected to increase by more than

summer precipitation, on the order of 5-10 percent during 2046-2065 and 10-15 percent during 2080-2099. Regionally, within the 12 grid boxes discussed in Section 4 that cover most of Pennsylvania, projected changes in temperature and precipitation are expected to be similar.

The importance of summer weather to agriculture is obvious. Winter weather is also important because it affects such things as soil moisture and temperature during the spring planting season, the extent of flooding of farm fields in the spring, and overwintering of crop and livestock pests.

The climate projections indicate an increase in the annual maximum number of dry days in Pennsylvania, one indicator of drought. The current number as simulated by the climate models is about 14 days. It is projected to rise on the order of 1-2 days during 2046-2065 and 1-4 days during 2080-2099, depending on the climate scenario. At the same time, three indicators of the intensity of precipitation in Pennsylvania are also projected to increase: the number of days in a year with precipitation exceeding 10 mm; the annual maximum 5-day precipitation total; and the fraction of annual precipitation that arrives in daily events that exceed the historical 95th percentile. In sum, as Section 4 indicates, Pennsylvania's hydrological climate may become more extreme in the future, with longer dry periods and greater intensity of precipitation.

Pennsylvania agriculture will be impacted not only by changes in its own climate but also by changes in climate in other agricultural production regions of the nation and world (Abler and Shortle 2000). These are indirect effects of climate change as discussed in the Introduction. As national and global agricultural markets adjust to these changes in production, commodity prices facing Pennsylvania farmers could change. As discussed in other sections of this report, climate change may also have impacts on nonagricultural sectors of the Pennsylvania economy, and economies of other states and countries. These changes might manifest themselves as changes in prices of purchased inputs used by Pennsylvania farmers, in competing demands for land within Pennsylvania, or alternative employment opportunities available to Pennsylvania farmers. Indirect impacts such as these are important because they can amplify or counteract direct impacts of climate change within Pennsylvania, and they may even have greater impacts for Pennsylvania agriculture than the direct impacts (Abler et al. 2000).

The recent IPCC report on food, fiber and forest products (Easterling et al. 2007) projects that global food production potential may increase with increases in local average temperature in agricultural production regions over a range of 1-3 degrees C, but above this range may decrease. This IPCC report also summarizes results from five economic modeling studies of the effects of different degrees of global mean temperature change on real global cereal prices. Over the range of 1-3 degrees C, higher global food production may result in a small decline in real global cereal prices. The average of results from the five studies is in the neighborhood of a 0-5 percent decline in prices. However, all five studies project that cereal prices will rise if temperature increases are 5 degrees C or greater. At an increase of 5.5 degrees C, the average of the five studies is a rise in real global cereal prices of nearly one-third (30 percent).

9.3.1 Feed Crops

Statistics from the *2007 Census of Agriculture* indicate that the three most important feed crops in terms of acreage in Pennsylvania are hay, corn (for grain and for silage), and soybeans, and the most important in terms of sales are corn and soybeans. This section focuses on these crops.

Elevated levels of CO_2 may lead to an increase in photosynthesis and thus yields of these three crops, a phenomenon often called the CO_2 fertilization or enrichment effect. Carbon dioxide is an indispensable component in the process of process of photosynthesis. The IPCC report on food, fiber and forest products (Easterling et al. 2007) concludes that, at 550 ppm atmospheric CO_2 concentrations, yields may increase under unstressed conditions due to the CO_2 fertilization effect relative to present-day CO_2 concentrations. The effect is expected to be stronger (on the order of 10-25 percent) for C_3 crops than for C_4 crops (0-10 percent).[6] However, the IPCC report cautions that "the effects of elevated CO_2 measured in experimental settings and implemented in models may overestimate actual field- and farm-level responses, due to many limiting factors such as pests, weeds, competition for resources, soil, water and air quality, etc., which are neither well understood at large scales, nor well implemented in leading models" (p. 282).

Most crops grown in Pennsylvania and worldwide are C_3 crops. C_3 feed crops include soybeans and different types of hay, among them alfalfa, timothy, tall fescue, orchardgrass, and perennial ryegrass. C_3 food crops include wheat, barley, fruits, vegetables, and potatoes. C_4 crops include corn and sorghum.

CO_2 fertilization effects may promote the growth of weeds, limiting yield increases for crops and/or leading farmers to apply more herbicides or do more mechanical weeding. Most of the worst weeds worldwide are C_4 plants, although many weeds currently affecting Pennsylvania agriculture are C_3 plants, including common lambsquarters, common ragweed, velvetleaf, and common chickweed. Warming can be expected to lead to a northern expansion of tropical and other warm-season weeds such as kudzu. If no herbicides are used, yield losses due to weeds are significantly greater in the southern U.S. than in the north for both corn and soybeans, which may be related to the presence of aggressive weeds in the south such as kudzu (Wolfe et al. 2008). Crop-weed interactions are complex, and one cannot say with any confidence whether climate change and CO_2 fertilization effects will favor crops relative to weeds or vice versa (Pritchard and Amthor 2005).

Warming may lead to a northern expansion of plant parasitic nematodes, and insects, presenting Pennsylvania agriculture with a different set of pest challenges than it faces today. Warming may also increase populations of marginally overwintering insect

[6] In the first step of photosynthesis, C_3 plants convert the carbon from carbon dioxide into a three-carbon molecule, while C_4 plants convert it into a four-carbon molecule.

species such as corn flea beetles (Wolfe et al. 2008). Insect pests may develop more quickly in a warmer climate, and multivoltine insects might be able to complete more life cycles during a year (Pritchard and Amthor 2005). On the other hand, if droughts become more frequent, the pressure and spread of many insects could decline (Wolfe et al. 2008). Natural enemies of crop pests such as birds and beneficial insects might benefit from a warmer climate (Pritchard and Amthor 2005). We cannot say with any confidence whether climate change will favor crop pests relative to birds and beneficial insects, or vice versa.

Some information about the potential impacts of a warmer climate on hay, corn, and soybean yields can be obtained by examining yields in Pennsylvania and states to the south using data from USDA's National Agricultural Statistics Service (2009b). We calculated average yields over a 20-year period (1989-2008).

This "southern states" analogue is not perfect because there are many other variables that affect yields such as precipitation, extreme weather events, solar irradiation, soils, irrigation, and farm management practices. As discussed earlier in this report, the difference in geographic location between Pennsylvania and southern states (the proximity of the Great Lakes and Pennsylvania's location with respect to North American storm tracks) means that Pennsylvania's future winters will be different from any analogues we might suggest from today. Still, this procedure does permit us to see what yields are like in a warmer climate where farmers have had many years to adapt to that climate.

Moderate climate change on the order of a 1-3 degrees C increase in average annual temperature in southeastern Pennsylvania, where most of Pennsylvania's agriculture is located, would make it similar to present-day Maryland. Significantly greater climate change on the order of a 5-6 degrees C increase in average annual temperature would make it close to that of present-day northern Georgia.

In the case of corn for grain, the average yield during 1989-2008 for Pennsylvania was 109 bushels/acre (6.8 metric tons/hectare). The average in Maryland was 116 bushels/acre, higher than Pennsylvania, but states to the south of Maryland were lower than Pennsylvania: 104 in Virginia, 96 in North Carolina, 81 in South Carolina, and 106 in Georgia. For soybeans, the average yield for Pennsylvania was 38 bushels/acre (2.6 metric tons/hectare). Average yields in states to the south of Pennsylvania were all lower: 33 in Maryland, 30 in Virginia, 28 in North Carolina, 23 in South Carolina, and 25 in Georgia. For alfalfa, the average yield for Pennsylvania was 2.9 tons/acre (6.5 metric tons/hectare). The average yield in Maryland was 3.7 tons/acre; in Virginia, 3.3; and in North Carolina, 2.7. No yield data are available for South Carolina or Georgia, where very little alfalfa is grown. Farmers in those states grow other types of hay such as orchardgrass, bermudagrass, and tall fescue. Figures 9.8 and 9.9 illustrate yields of feed crops and alfalfa by state.

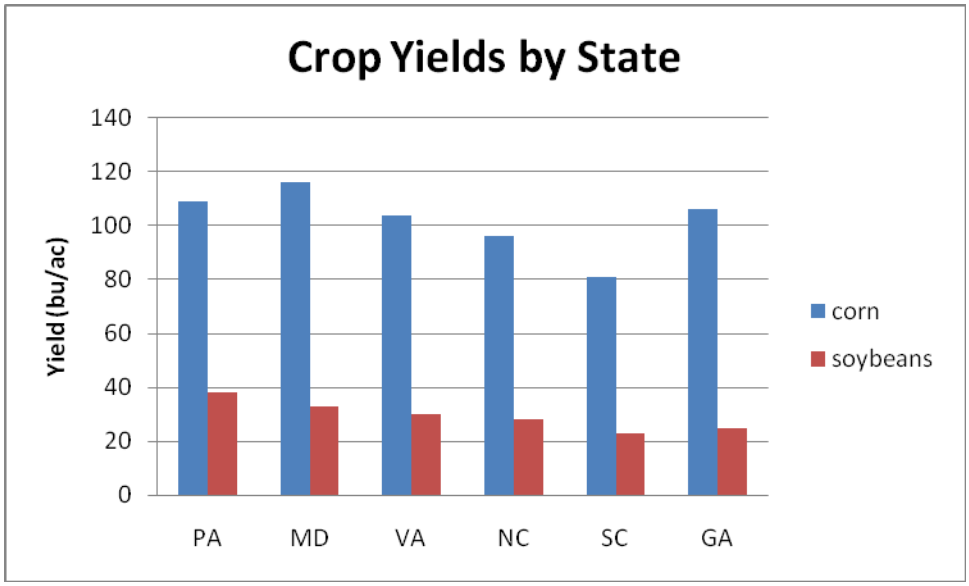


Figure 9.8. Feed Crop Yields by State

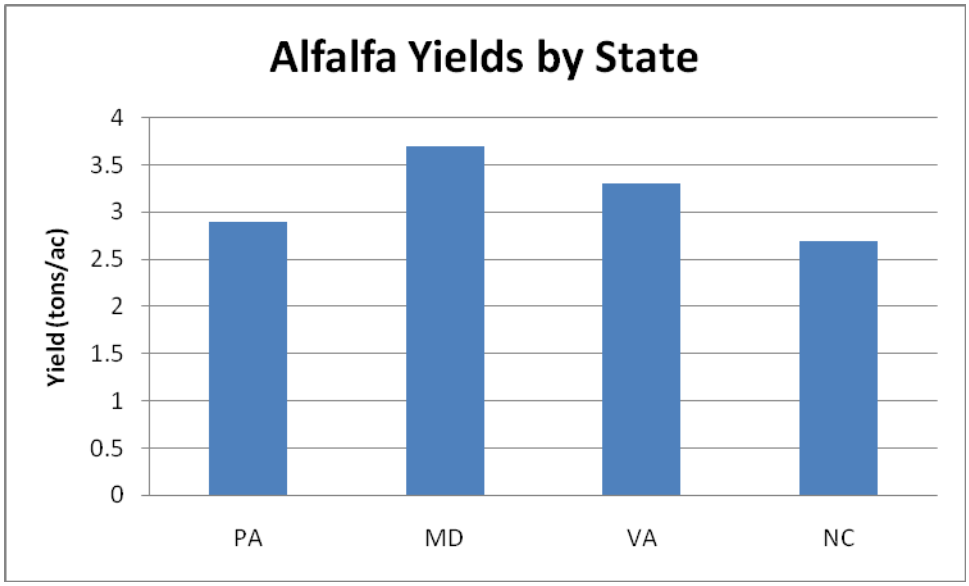


Figure 9.9. Alfalfa Yields by State

McCarl, Villavicencio and Wu (2008) conducted a detailed econometric analysis of the effects of climate on U.S. yields for corn and soybeans, among other crops. They controlled for the effects of technological change on crop yields. Using projections of climate change for 2030, they found that corn yields in the Northeast could rise by about 30 percent and soybean yields could rise by 18-28 percent. They projected yield increases for corn and soybeans in other regions of the U.S. as well.

In sum, moderate climate change on the order of 1-3 degrees C may raise Pennsylvania yields of hay, corn, and soybeans, but it may also raise yields elsewhere in the U.S. and around the world, increasing global production and pushing down prices received by Pennsylvania farmers. The net effect on Pennsylvania farm revenues for these crops is likely to be small—either a small increase or a small decrease. Greater climate change could lower Pennsylvania yields of these crops, but it could also lower yields elsewhere, reducing global production and raising prices received by Pennsylvania farmers. Again, the net effect on Pennsylvania farm revenues for these crops is likely to be ambiguous.

9.3.2 Food Crops

Pennsylvania produces a wide range of food crops. Statistics from the *2007 Census of Agriculture* indicate that one major food crop in terms of sales in Pennsylvania is mushrooms, and mushrooms are the only food crop among the top seven agricultural product categories in terms of sales in Pennsylvania.[7] Mushroom sales in 2007 were $487 million. Important food crops in Pennsylvania also discussed in this section are fruits, tree nuts and berries (sales of $151 million) and vegetables, melons and potatoes (sales of $126 million).

Mushrooms are almost entirely cultivated inside of specialized growing houses under carefully controlled temperature and humidity, with different temperatures required depending on the stage of the cultivation process and the type of mushroom being produced. Humidity is generally maintained at a high level throughout the process, which can take roughly three months from preparation of the compost in which the mushrooms are grown through to harvesting. There are no firm statistics for Pennsylvania, but statistics for the U.S. as a whole suggest that less than 5 percent of mushroom sales currently come from mushrooms grown outdoors in the woods (USDA, National Agricultural Statistics Service, 2008b). There are also a few mushroom farms in limestone caves or abandoned coal mines, but these are generally considered unreliable because of the difficulty of controlling climatic conditions.

The effects of climate change on mushroom production will primarily be manifested in changes in heating and cooling requirements for growing houses. As part of the preparation process, compost is pasteurized at about 60 degrees C for two hours or more in order to eradicate harmful bacteria, nematodes, insects, and fungi. Higher average outdoor temperatures will lower heating requirements during the pasteurization process. Because multiple crops of mushrooms can be grown and harvested indoors during a single year, the effects of climate change on other stages of the mushroom growing process will depend on the season in which the mushrooms are being grown. Many temperate mushrooms require ambient temperatures of 21-27 degrees C during the spawning and growth stage, which typically lasts two to three weeks. With climate change, there will on average be less heating required during the winter months but additional cooling during the summer months. The net effects on annual energy use and

[7] The top-seven list in order of sales, as mentioned above, is: dairy; poultry and eggs; cattle and calves; mushrooms; other nursery and greenhouse products (aside from mushrooms); hogs and pigs; and corn. These seven product categories account for 86 percent of total agricultural product sales in Pennsylvania.

annual production costs are unclear, and we cannot say with any confidence whether they will increase or decrease.

For fruits and vegetables, an increase in summer heat stress may be damaging to cool temperature-adapted crops such as apples and potatoes (Wolfe et al. 2008). Fruits such as apples and grapes have a winter chilling requirement of 200-2,000 cumulative hours within a narrow temperature range, typically 0-10 degrees C (Wolfe et al. 2008). Temperatures outside of this range generally do not meet this chill requirement. Among grapes, native American varieties (*Vitis labruscana*) have a much longer chilling requirement than European varieties (*Vitis vinifera*) (Wolfe et al. 2008). European varieties, on the other hand, do poorly if temperatures drop below about minus 9 degrees C (15 degrees F) during the winter. In a warmer climate, Pennsylvania wineries may choose to replace some of their native American grape varieties with European varieties. This would entail costs in removing current vines and replanting them with new ones. It would also entail benefits because wines from European varieties command higher prices on average than those from American varieties.

An increase in the frequency of droughts may be damaging to fruits and vegetables that are vulnerable to quality defects, such as blossom end rot in tomato, caused by hourly and daily fluctuations in water availability (Wolfe et al. 2008). Quality is important for any crop but particularly so for fresh fruits and vegetables, where blemishes or defects may significantly lower the price received or even render the product unsalable. At the same time, because fruits, vegetables and potatoes are C_3 crops, the CO_2 fertilization effect may at least partially offset yield declines due to changes in temperature and precipitation.

As with feed crops, information about the potential impacts of a warmer climate on fruit, vegetable and potato yields can be obtained by examining yields in Pennsylvania and states to the south using data from USDA's National Agricultural Statistics Service (2009b). As noted above, within the vegetable-melon-potato product category, the most important crop in Pennsylvania in terms of acreage is currently sweet corn, followed by potatoes. The most important product in the fruit-tree nut category in terms of acreage is apples. We calculated average yields over a 20-year period (1989-2008) for potatoes. For sweet corn and apples, where yield data are more limited, we used a nine-year period (2000-2008), dropping the high and low years during this period for each state when calculating the average.[8]

The average yield of sweet corn during 2000-2008 in Pennsylvania, after dropping high and low years, was 3 tons/acre (6.7 metric tons/hectare). Average yields in states to the south of Pennsylvania were all higher: 3.3 tons/acre in Maryland, 3.4 in Virginia, 4.8 in North Carolina, and 6.7 in Georgia (no yield data on sweet corn were available for South Carolina). The average yield of potatoes during 1989-2008 for Pennsylvania was 11.8 tons/acre (27 metric tons/hectare). Average yields in states to the south were all lower: 11.5 tons/acre in Maryland, 10.1 in Virginia, and 9.1 in North Carolina. No yield data are

[8] The data for apples are from various issues of the National Agricultural Statistics Service's *Noncitrus Fruits and Nuts* report.

available for South Carolina or Georgia, where very few potatoes are grown. The average yield for apples during 2000-2008 in Pennsylvania, after dropping high and low years, was 10.4 tons/acre (23 metric tons/hectare). Average yields in states to the south were all lower: 7.6 tons/acre in Maryland, 9.5 in Virginia, 10.3 in North Carolina, 3.1 in South Carolina, and 4.9 in Georgia. Figure 9.10 displays selected food crop yields by state.

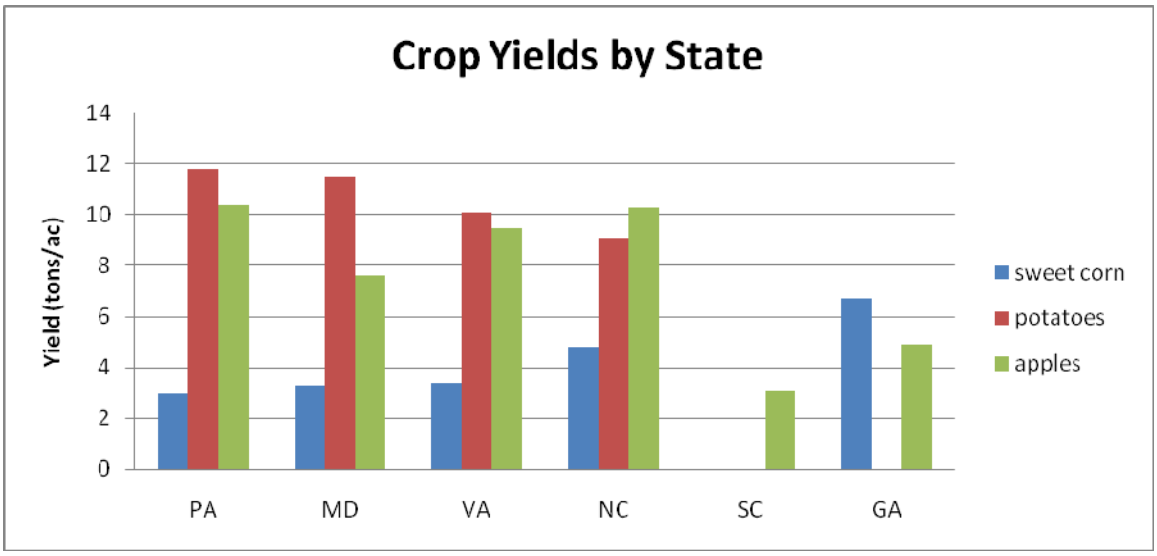


Figure 9.10. Food Crop Yields by State

Warmer temperatures will permit some of Pennsylvania's food crop producers to grow a wider variety of crops by day length, particularly sweet corn. This will allow sweet corn producers to deliver their product to market earlier in the year, increasing their competitiveness with corn grown in southern states that have traditionally dominated the early summer market for sweet corn. The result is likely to be an increase in revenues accruing to Pennsylvania's sweet corn growers.

In sum, the effects of climate change on mushroom production are ambiguous. Yields of cool-temperature adapted fruits and vegetables such as potatoes and apples are likely to decline as a result of climate change, while yields of fruits and vegetables better suited to a warmer climate such as sweet corn are likely to rise. Pennsylvania farmers are likely to adapt to climate change by changing the types and varieties of fruits and vegetables grown.

9.3.3 Other Crops

Statistics from the *2007 Census of Agriculture* indicate that annual Pennsylvania sales of other nursery and greenhouse products (aside from mushrooms) are $406 million, making it one of the top seven agricultural product categories in terms of sales in Pennsylvania. The two most important products within this category are bedding/garden plants ($161

million in sales) and nursery stock ($108 million in sales). Other important products include potted plants, greenhouse tomatoes, and cut flowers.

For bedding/garden plants and nursery stock, climate change is likely to necessitate changes in the types of species that are grown and sold to consumers. There is unlikely to be a significant threat to the economic health of the industry—there will still be a demand for landscaping products in a warmer climate, just as there is in southern states today. The USDA's Plant Hardiness Zone Map was last updated in 1990, but the Arbor Day Foundation released its own updated map in 2006 showing that parts of many states have shifted by one hardiness zone since 1990 and some areas have shifted by two zones. Commercial nurseries can facilitate climate change adaptation by providing a head start for northward range shifts among plant species (Van der Veken et al. 2008).

For greenhouse tomatoes, it is hard to find locations in the U.S. where the climate makes production profitable in both the summer and winter (Cook and Calvin 2005). Currently there is significant winter greenhouse tomato production only in the west and southwest parts of the country. If winter temperatures rise significantly due to climate change, greenhouse heating costs in Pennsylvania might fall to the point where it becomes profitable to produce greenhouse tomatoes in the winter. Climate permitting, winter greenhouse production is more profitable than summer production because tomato prices are significantly higher in the winter (Cook and Calvin 2005). The question in this case is whether summer production would continue to be profitable in the face of higher summer temperatures. Moreover, heating costs for winter greenhouse tomatoes grown in other states would also fall, putting downward pressure on market prices.

As noted above, hardly any crops in Pennsylvania are currently used as energy crops. If energy crops were to become important in the future, their yields would likely be affected by CO_2 fertilization effects and changes in temperature and precipitation. Two potential energy crops that are currently major feed crops in Pennsylvania, corn and soybeans, are discussed above. However, it should be noted that Pennsylvania is currently a net importer of corn from other states, so that corn-based ethanol production in Pennsylvania could imply either greater corn imports, reduced corn usage by Pennsylvania livestock producers, or both. Research to date on climate change and switchgrass is very limited, but one study of Midwest states suggests that CO_2 fertilization effects and higher temperatures could raise switchgrass yields (Brown et al. 2000). On the other hand, a study of Upper Southeastern states found generally weak or no effects of temperature and precipitation on switchgrass yields (Fike et al. 2006).

9.3.4 Livestock Products

Statistics from the *2007 Census of Agriculture* indicate that four livestock products are among the top seven agricultural product categories in Pennsylvania in terms of sales: dairy, poultry and eggs, cattle and calves, and hogs and pigs. This section focuses on these livestock products.

Like all warm-blooded animals, livestock require ambient temperatures that allow them to maintain a relatively constant body temperature (Boesch 2008). If their body temperature moves outside of their normal range, they must expend energy to conserve or eliminate heat. This reduces energy that can be devoted to production of products such as milk, bodily growth, and reproduction. Heat stress can lead to reduced physical activity, reduced eating or grazing, and higher livestock mortality. Temperature thresholds vary according to the species of livestock and each individual animal's genetics and health.

In Pennsylvania dairy and cattle production, livestock are often outdoors much of the time. Dairy cows prefer cool temperatures, with the optimum temperature range for milk production being 4.5-23.8 degrees C (40-75 degrees F) (Wolfe et al. 2008). An increase in the average summer temperature of 5-6 degrees C could lead to heat-stress losses of 10-25 percent reduction in milk production (Wolfe et al. 2008). Beef cattle have a somewhat greater tolerance for heat, but an increase in the average summer temperature on the order of 5-6 degrees C could place significant heat stress on them as well.

Poultry and eggs in Pennsylvania are mostly produced in large-scale indoor facilities where the birds are kept in close quarters. Housing large numbers of birds with a high metabolism in these conditions makes them vulnerable to heat stress during the summer (Boesch 2008). Birds can be at least partially protected against heat stress through investments in insulation, ventilation, fans and air conditioning in growing facilities. The existence of large-scale poultry production in southern states such as Alabama, Arkansas, Georgia, and Mississippi suggests that these investments can be made at acceptable cost, at least with current energy prices. Higher energy prices might alter that calculation.

Adult hogs prefer cooler temperatures, with the optimum temperature range for adult hog growth being 13-21 degrees C (55-70 degrees F). Baby pigs must be kept warmer, with optimum temperatures between 29-32 degrees C (85-90 degrees F). Hogs and pigs in Pennsylvania are typically housed inside of growing facilities, with ventilation and fans used to keep hogs cool during the summer. During very high summer temperatures, producers will sometimes spray water on their hogs to keep them cool. Facilities should be well-ventilated year round to avoid pigs breathing stale air that can transmit disease. With climate change, heating costs will fall during warmer winters but costs of keeping animals cool during the summer will rise. The net effects on annual energy use and annual production costs are unclear. However, the existence of large-scale hog production in southern states such as North Carolina and Oklahoma suggests that Pennsylvania hog production is likely to continue being economically viable in a warmer climate.

Currently, a large portion of poultry and hog production is concentrated in warmer, more southern states. These operations were originally located in these states when energy prices and average temperatures were lower than they are today. The concentration may have occurred due to a clustering effect, since these sectors depend highly on the availability of specialized products and services that can be supplied more efficiently to a large number of farms than a small number. Since climate control is a substantial input into the growth of these livestock, climate change may stimulate the movement of poultry

and hog production northward into states like Pennsylvania. Given the highly clustered nature of these industries, the movement could be large-scale rather than incremental.

Climate change is also likely to impact livestock production through parasites, pathogens, and disease vectors (Boesch 2008). There may be northward migration of livestock pests currently found in southern states and greater overwintering of pests already present in Pennsylvania. Pennsylvania livestock producers will likely face a different set of pest and disease management challenges than they face today, but we cannot say with any confidence whether the challenges will be greater or smaller.

Like food and feed crops, some information about the potential impacts of a warmer climate on cow milk yields can be obtained by examining yields in Pennsylvania and states to the south using data from USDA's National Agricultural Statistics Service (2009b). We calculated average yields over a nine-year period (2000-2008). As with crops, this southern states analogue is imperfect because there are many other variables that affect milk yields such as feed quality, breeding, and other farm management practices. Like crops, though, this procedure permits us to see what yields are like in a warmer climate where farmers have had many years to adapt to that climate. The average milk yield in Pennsylvania during this period was 18,588 pounds/cow (8,430 kg/cow). Average yields to the south of Pennsylvania were all lower, but there is no clear relationship between a state's latitude and its milk yield: Maryland's yield was 16,486 pounds/cow; Virginia 16,555; North Carolina 17,991; South Carolina 17,032; and Georgia 17,286. Figure 9.11 displays milk yields by state.

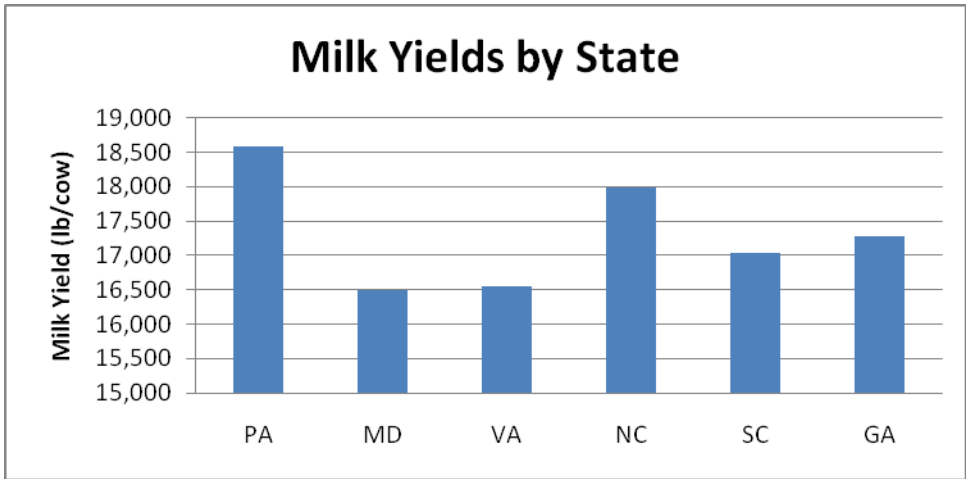


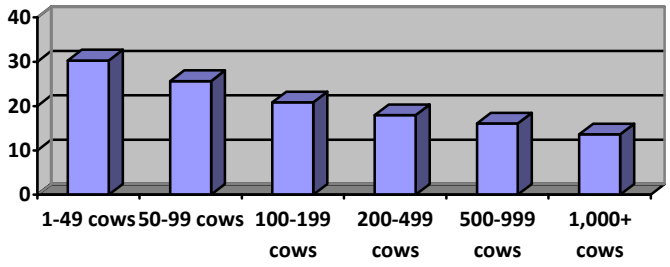
Figure 9.11. Milk Yields by State

For livestock destined for slaughter (cattle and calves, hogs and pigs, and broilers), the concept of yield is not meaningful for assessing climate change impacts. Barring disease outbreaks, producers have a high degree of control over weight gain in these animals depending on how long the animals are kept, what they are fed, how much they are fed, and their level of physical activity. However, the cost to producers of growing their animals to market weight may be affected by climate change.

Cost-of-production data for various livestock products are available at the state or regional level from the USDA's Economic Research Service. However, using these data to estimate the effect of climate on production costs is confounded by the many other factors that influence costs, including differences between states in the scale of farm operations. Many farm operations are subject to economies of scale. For example, Pennsylvania's cost of milk production (operating costs plus overhead costs) was $22.61 per hundredweight in 2005, compared with $18.48 in Georgia (USDA, Economic Research Service 2009b). The average number of milk cows per dairy farm in 2005 was 85 in Pennsylvania, compared with 273 in Georgia. Dairy farms in other southern states for which statistics are available also have larger average herd sizes than Pennsylvania—125 in Virginia, 403 in Texas, and 1,013 in Florida.

Across all states, the cost of milk production was $25.61 per hundredweight for farms with 50-99 cows versus $17.95 for farms with 200-499 cows. Among farms with 1,000 cows or more, the cost of production dropped to $13.62. Figure 9.12 illustrates the economies of scale associated with larger dairy operations.

Figure 9.12. Milk Costs of Production ($/hundredweight)



Pennsylvania livestock production may also be impacted by climate change through changes in pasture production and quality, on-farm production of feed crops, and changes in prices of purchased feed. The recent IPCC report on food, fiber and forest products (Easterling et al. 2007) concludes that effects of elevated CO_2 levels on pasture production and quality may be mixed. Effects of changes in temperature and precipitation on pastures are more difficult to project due to a lack of research on the types of pasture plants grown in Pennsylvania. Longer growing seasons created by warmer temperatures would allow dairy and cattle producers to graze their livestock for more of the year, reducing expenses on purchased feed and the amount of feed crops that need to be grown on the farm.

As noted above, moderate climate change on the order of 1-3 degrees C may raise Pennsylvania yields of feed crops (hay, corn, and soybeans), but it may also raise yields elsewhere in the U.S. and around the world, increasing global production and pushing down prices of these crops. Both of these developments would be beneficial to livestock

producers, who would see their on-farm production of feed crops rise and their costs of purchased feed fall. However, greater climate change could have opposite effects.

With regard to alfalfa, perhaps more important than overall yields are changes in crop quality. A wetter climate may lead to higher levels of neutral detergent fiber in alfalfa that could reduce the ability of dairy cows to convert the feed into milk.

In sum, the effects of climate change on Pennsylvania livestock producers are likely to be mixed. In the dairy industry, heat stress and a decline in feed quality are likely to drive milk yields downward and increase production costs. For operations that rely on grazing and on-farm production such as dairy and beef herds, changes in pasture yields and feed quality will impact production costs. At moderate levels of warming, this effect may be positive; however, higher temperature rises may have a negative impact. For the state's hog and poultry producers, while climate control costs are likely to increase with warmer summer months, this same effect in southern states may make Pennsylvania more attractive to these industries and could induce a northward shift in production operations.

9.3.5 Agriculture and Environment

The primary function of agriculture is to supply food, fiber, energy and industrial products. However, agriculture can also be a source of several public goods and externalities. People value agricultural land as open space and a source of countryside amenities. Agricultural land is a frequently a habitat for wildlife species. The agricultural sector can contribute to the economic viability of many rural areas and to food security. On the other hand, conversion of forests and wetlands to agricultural production can damage ecosystems. Agricultural nutrients, pesticides, pathogens, salts, and eroded soils are leading causes of water quality problems in many areas worldwide. Water used for irrigation in agriculture is water unavailable to non-agricultural sectors or ecosystems. There is concern about the effects of livestock production on animal welfare. On both the positive and negative side, agriculture can be both a sink and a source for greenhouse gases.

Abler et al. (2002) studied the potential effects of climate change on deliveries of nitrogen to the Chesapeake Bay from corn farms in Pennsylvania. They found that the impacts of climate change were highly sensitive to assumptions about the existence or absence of CO_2 fertilization effects and whether corn prices change due to the worldwide effects of climate change on agricultural production. The results are split on the direction of change in water quality. However, there is an asymmetry in terms of the magnitude of change in nitrogen deliveries to the Chesapeake Bay. In the case where corn prices do not change, the largest fall in nitrogen deliveries among the scenarios considered is only 3 percent, while the largest rise is 13 percent. In the case where corn prices do change, the largest fall in nitrogen deliveries is 33 percent, while the largest rise is 57 percent.

One factor not considered in the Abler et al. (2002) study is the potential impact of climate change on expansion or contraction of Pennsylvania's poultry and livestock industries. If the operations currently in southern states migrate northward to

Pennsylvania as a result of climate change, pressures on water quality from nutrient pollution in Pennsylvania might increase, depending on manure storage, utilization and disposal practices.

Neff et al. (2000) made projections of future streamflow, groundwater, and water quality in the Mid-Atlantic region under different climate scenarios. They found that nutrient loads in surface waters may increase during winter and spring because of an expected increase in streamflow. They also found that streamflow and associated nutrient fluxes may decrease in July and August, which could reduce problems associated with estuarine stratification and eutrophication in late summer.

The evolving weed and insect management challenges created by climate change may lead farmers to apply different types of pesticides, and in different quantities, than today. Whether these changes will be beneficial or harmful for the environment is unclear. It is possible that genetic engineering during coming decades may improve the pest resistance of crops to the point where insecticide usage is significantly reduced, just as insect-resistant (Bt) varieties of corn to control the corn borer and corn rootworm are already on the market.

9.4 Adaptation Options

The existence of a productive and dynamic agriculture in states to the south of Pennsylvania demonstrates that Pennsylvania agriculture can continue to prosper in a warmer climate, but changes will be required. Any producers who fail to adjust to climate change are likely to see their yields and profitability decline. Appendix 5 contains some estimates in this regard using the Integrated Farm System Model (IFSM) (Rotz et al., 2008). Fortunately, Pennsylvania agriculture is an industry very familiar with continual and rapid change.

We can state with high confidence that climate change will require changes in the types of crops that are grown in Pennsylvania. Alfalfa may decline in importance; if so, farmers will plant other types of hay better suited to a warmer climate. Farmers in South Carolina and Georgia grow types of hay such orchardgrass, bermudagrass, and tall fescue. Acreage devoted to cool-temperature fruits and vegetables such as potatoes and apples is likely to decline, while acreage devoted to crops better suited to a warmer climate such as sweet corn is likely to rise. One factor that could limit the decline in acreage devoted to cool-temperature fruits and vegetables is a demand for locally grown foods, if that demand increases significantly in coming decades. For bedding/garden plants and nursery stock, climate change is likely to necessitate changes in the types of species that are grown and sold to consumers. For grapes, Pennsylvania wineries may choose to replace some of their native American grape varieties with European varieties that do better in a warmer climate.

We can also state with high confidence that climate change will require changes in the varieties of crops that are grown. Corn and soybeans are major feed grains in Pennsylvania today and there is no reason to expect that to change in coming decades.

Farmers will need to plant corn and soybean varieties suitable to a warmer environment and better able to withstand a likely increase in the variability of temperature and precipitation.

With respect to small grains, the *2007 Census of Agriculture* shows progressively less barley acreage as one moves to states further south of Pennsylvania, with hardly any barley grown in South Carolina or Georgia. However, there is significant acreage of wheat, oats and rye in states to the south of Pennsylvania. Pennsylvania small grain farmers might adapt to climate change by cutting back on barley acreage and by planting varieties of wheat, oats and rye suited to a warmer climate. On the other hand, if climate change expands the potential for double cropping of barley and soybeans, there could be growth in barley acreage in Pennsylvania.

As mentioned above, the evolving weed and insect management challenges created by climate change may lead farmers to apply different types of pesticides, and in different quantities, than today. We cannot say with any confidence whether these changes will be beneficial or harmful for the environment. Some types of pesticides are less effective in controlling insects at higher temperatures (Wolfe et al. 2008).

Organic agriculture, which is growing as consumers demand more organic food products, may help farmers adapt to climate change. Organic practices that maintain or increase organic matter in soils may cause soils to retain significantly more rainwater due to the "sponge properties" of organic matter (Niggli, Schmid and Fliessbach 2007). This may be important insofar as climate change leads to a more extreme hydrological climate for Pennsylvania, with longer dry periods and greater intensity of precipitation. On the other hand, changes in weed and insect pest types and pest populations created by climate change might create challenges for organic producers.

The presence of longer dry periods may increase the use of irrigation for crops where it already exists and may make the practice economically viable for others. While drip irrigation technologies are well-developed, additional irrigation may pose challenges as more sources compete for limited water resources. Whether future irrigation practices will put pressure on Pennsylvania's water resources bears further investigation.

Producers of dairy products, cattle and calves, and hogs and pigs can adapt to climate change by selecting breeds that are genetically adapted to a warmer climate. Breeds that are more heat tolerant tend to be less productive (Boesch 2008). Warming may lead producers who currently keep their livestock outdoors much of the time to move them indoors into climate-controlled facilities, which would increase energy use and costs of production relative to present-day production systems (Boesch 2008). On the other hand, dairy and beef producers may benefit from a longer grazing season.

Among Pennsylvania farmers, dairy producers may experience the greatest challenges from climate change given their reliance on own-crop production, animal heat stress due to housing in the ambient environment, and impacts to forage quality that will affect productivity. If future global trade agreements lower U.S. tariffs on dairy products, dairy

producers in Pennsylvania will also be facing greater competition from New Zealand, Australia, and Argentina. The existence of productive and profitable dairy industries in states to the south of Pennsylvania suggests that Pennsylvania dairy farmers can adjust to a warmer climate, but they will likely need to enhance the efficiency of their operations to offset climate change impacts. Dairy farms in southern states today tend to have larger herd sizes than Pennsylvania dairy farms, allowing them to take greater advantage of economies of scale.

An increase in the variability of temperature and precipitation is likely to increase the demand by farmers for risk management products. As noted above, nearly one-fourth of Pennsylvania cropland was enrolled in crop insurance programs in 2007. This level of enrollment is well below the average for other states. New government programs serve to make crop-insurance more financially attractive, and there are substantial opportunities to improve profitability through crop insurance. Producers have a range of risk management products from which to choose, including yield insurance against losses due natural causes such as drought, excessive moisture, hail, wind, frost, insects, and disease; catastrophic loss insurance; gross revenue insurance that protects against gross revenue falling below a specified level; and adjusted gross revenue insurance that insures the revenue of an entire farm rather than a specific crop.

For agricultural products produced indoors—the most important in Pennsylvania being mushrooms, poultry and eggs, and hogs and pigs—climate change will lead to changes in heating and cooling costs. On average, there will be less heating required during the winter months but additional cooling during the summer months. The net effects on annual energy use and annual production costs are unclear. Additional investments in insulation, ventilation, fans and air conditioning in production facilities may be needed, but these investments can be made over a period of several years or even decades, during which time the facilities would likely need renovations or replacement anyway.

The ability of Pennsylvania agriculture to adapt to climate change hinges in part on the development and adoption of new crop varieties and livestock breeds suited to a warmer and more variable climate. Public- and private-sector agricultural research organizations will need employees with the scientific skills to develop these new varieties and the resources required to carry out this research. Time lags between the start of agricultural research and the introduction of new, commercially available products can easily reach 20 or 30 years (Alston, Craig and Pardey 1998), so this research will need to begin soon if it is to have an impact by 2030. These additional resources might potentially come at the expense of resources devoted to advancing agricultural technology in other ways.

9.5 Mitigation Barriers and Opportunities

Pennsylvania agriculture is a source of greenhouse gas emissions including CO_2 emissions from fossil fuel energy use, methane (CH_4) emissions from livestock and manure management, and nitrous oxide (N_2O) emissions from manure management and fertilizer (Rose et al. 2003). Pennsylvania agriculture also has three potential avenues for greenhouse gas mitigation: sequestration of atmospheric carbon in agricultural soils;

changes to agricultural practices that reduce greenhouse gas emissions; and production of biofuel crops that reduce the use of fossil fuels (Fisher et al. 2007, Schneider and Kumar 2008).

Options often mentioned for sequestering atmospheric carbon include conversion of cropland to forestry or pasture, planting of winter cover crops, reduced tillage practices, organic farming, and planting trees or biofuel crops on marginal agricultural land (Rosenzweig and Tubiello 2007, LaSalle and Hepperly 2008, Carbon Management Advisory Group 2008). Estimates of the amount of carbon that might be sequestered by these options vary significantly (Rosenzweig and Tubiello 2007).

Changes in agricultural practices that could reduce greenhouse gas emissions include reduced fossil fuel use, changes in manure storage and handling practices, improving crop residue management, and use of low-emission fertilizers. However, the potential for cuts in greenhouse gas emissions by Pennsylvania agriculture to make a significant contribution to overall emission reduction goals is limited because agriculture only accounts for about 2 percent of Pennsylvania's total greenhouse gas emissions (Carbon Management Advisory Group 2008).

One option that could reduce greenhouse gas emissions and provide a source of energy is constructing manure digester and methane recovery facilities at confined animal feeding operations (CAFOs). Following recovery, the methane is cleaned of impurities and converted to electricity via an engine-generator set, which can be used on the farm or added back to the grid. A favorable electricity price guaranteed over a long term would make a major contribution to the economic viability of manure digester operations. The costs of such a program could be outweighed by the benefits of reduced greenhouse gas emissions and odor reductions associated with agricultural operations.

Pennsylvania farmers already engage in many of these practices to varying degrees, but a carbon cap-and-trade program or a carbon tax would likely increase their usage. Either policy would put a price on carbon, giving farmers incentives to adjust their production practices. Lewandrowski et al. (2004) find that U.S. farmers would choose different types of mitigation strategies depending on the price of carbon. At a price of $10 per metric ton of permanently sequestered carbon, farmers would mainly adopt conservation tillage as their mitigation strategy. At prices of $25 or higher, significant amounts of cropland might be converted to forest. Lewandrowski et al. (2004) do not project significant conversion of cropland to pasture, mainly because they conclude that conversion to forest would sequester more carbon and hence be more profitable.

There are potential synergies between climate change adaptation and mitigation in agriculture (Rosenzweig and Tubiello 2007). For example, drought-resistant crop varieties help ensure a consistent year-to-year availability of crop residues, which are one possible future source of biofuels. Low-till and no-till production conserves soil moisture, which facilitates climate change adaptation by increasing resistance to drought. Mulches between rows of crops help conserve soil moisture and sequester carbon, promoting both adaptation and mitigation.

On the other hand, an increase the frequency of extreme weather events may have a negative effect on soil carbon sequestration by reducing production and worsening soil quality. Future soil carbon sequestration potentials under climate change may be much different than current estimates because of interactions between climate and soil dynamics (Rosenzweig and Tubiello 2007).

9.6 Information Needs

With regard to feed crops and feed cropping systems, it is likely that different varieties of corn and soybeans will need to be planted if growing seasons become longer and weather more variable. While a vast array of varieties of these crops already exists as evidenced by their cultivation across a range of climatic conditions, it will be necessary to identify and improve crop varieties specific to Pennsylvania's future climate. Parallel to this effort is the development of climate models with greater resolution that are able to predict climate variables on smaller geographic scale.

While corn and soybean production are likely to remain dominant, the effects of climate change on the prevalence of alfalfa are uncertain. Alfalfa is a leguminous crop that fixes nitrogen in the soil. The loss of an alfalfa crop would require farmers to plant some other legume or apply more nitrogen. More investigation is necessary to determine how alfalfa yields and quality are likely to change, and how these impacts will affect the rest of the crop mix.

With respect to dairy and beef operations, research is necessary to determine more precisely how pasture systems will be affected by a changing climate. Identifying and adapting pasture species for optimal livestock performance under future climate conditions could serve to ameliorate the impacts to operations that rely on grazing.

Just as changes in climate can alter crop species suitable for growth, they may also change the types of weeds and pests that can survive under the new climatic conditions. Research into this area is limited and should be expanded to identify what the new weed and pest species are likely to be as well as how best to address them. Improvements in genetic engineering could serve to overcome many of these challenges.

Research is needed not only on individual crop and livestock products but also on how each of them fits with the others in a dynamic cropping system. Continuous cropping systems have many environmental as well as economic benefits and identifying win-wins here could allow Pennsylvania's farmers to address climate change while improving productivity and reducing the environmental impacts associated with crop production. This will require a coordinated effort from the entire agricultural community.

Better quantification of N_2O reductions through reduced tillage practices would facilitate their acceptance by the carbon life cycle assessment community and allow for a value to be placed on nitrous oxide emissions. This would not only reduce greenhouse emissions but would have the additional environmental benefits of reduced runoff and fewer

emissions associated with field travel, since no-till or minimum tillage practices require fewer passes over a field. In parallel to this effort should be one to accurately measure the carbon sequestered from continuous cropping systems and reduced tillage practices.

9.7 Conclusions

The existence of a productive and dynamic agriculture in states to the south of Pennsylvania demonstrates that Pennsylvania agriculture can continue to prosper in a warmer climate, but changes will be required. Any producers who fail to adjust to climate change are likely to see their yields and profitability decline. Fortunately, Pennsylvania agriculture is an industry very familiar with continual and rapid change.

Moderate climate change on the order of 1-3 degrees C (2-5 degrees F) may raise Pennsylvania yields of hay, corn, and soybeans, but it may also raise yields elsewhere in the U.S. and around the world, increasing global production and pushing down prices received by Pennsylvania farmers. The net effect on Pennsylvania farm revenues for these crops is likely to be small—either a small increase or a small decrease. Greater climate change could lower Pennsylvania yields of these crops, but it could also lower yields elsewhere, reducing global production and raising prices received by Pennsylvania farmers. Again, the net effect on Pennsylvania farm revenues for these crops may be ambiguous.

With respect to the food crops that are grown in Pennsylvania, the effects of climate change on mushroom production are ambiguous. Yields of cool-temperature adapted fruits and vegetables such as potatoes and apples are likely to decline as a result of climate change, while yields of fruits and vegetables better suited to a warmer climate such as sweet corn are likely to rise. Pennsylvania farmers are likely to adapt to climate change by changing the types and varieties of fruits and vegetables grown. Pennsylvania wineries may choose to replace some of their native American grape varieties with European varieties. This would entail up-front costs in replacing vines but could be beneficial in the long run because wines from European varieties tend to command higher prices than wines from native American varieties.

For bedding/garden plants and nursery stock, climate change is likely to necessitate changes in the types of species that are grown and sold to consumers. There is unlikely to be a significant threat to the economic health of the industry—there will still be a demand for landscaping products in a warmer climate, just as there is in southern states today.

Hardly any crops in Pennsylvania are currently used as energy crops. If energy crops were to become important in the future, their yields would likely be affected by CO_2 fertilization effects and changes in temperature and precipitation. Two potential energy crops that are currently major feed crops in Pennsylvania, corn and soybeans, are discussed above. Research to date on climate change and switchgrass is very limited.

The effects of climate change on Pennsylvania livestock producers are likely to be mixed. In the dairy industry, heat stress and a decline in feed quality are likely to drive milk yields downward and increase production costs. For operations that rely on grazing and on-farm production such as dairy and beef herds, changes in pasture yields and feed quality will impact production costs. At moderate levels of warming, this effect is likely to be positive; however, higher temperature rise will probably have a negative impact. For the state's hog and poultry producers, while climate control costs are likely to increase with warmer summer months, this same effect in southern states may make Pennsylvania more attractive to these industries and could induce a northward shift in production operations.

Among Pennsylvania farmers, dairy producers may experience the greatest challenges from climate change given their reliance on own-crop production, animal heat stress due to housing in the ambient environment, and impacts to forage quality that may affect productivity. If future global trade agreements lower U.S. tariffs on dairy products, dairy producers in Pennsylvania will also be facing greater competition from New Zealand, Australia, and Argentina. The existence of productive and profitable dairy industries in states to the south of Pennsylvania suggests that Pennsylvania dairy farmers can adjust to a warmer climate, but they will likely need to enhance the efficiency of their operations to offset climate change impacts. Dairy farms in southern states today tend to have larger herd sizes than Pennsylvania dairy farms, allowing them to take greater advantage of economies of scale.

Crop and livestock and producers are likely to encounter changing pest, weed, and disease management challenges. Just as a changing climate may require new crop and animal species in production, it may also make the environment suitable for different species of insects and weeds as well as types of disease. Improvements in genetic engineering of crops and livestock may ameliorate these issues.

Climate change poses substantial challenges to Pennsylvania agriculture but it also offers opportunities. While the adoption of new technologies and management practices will be required for producers to adapt to a changing climate, change is the norm in agriculture. By identifying the key areas that need attention and taking steps today to overcome these obstacles, we can ensure that Pennsylvania agriculture remains vibrant for decades to come.

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10.0 Energy

10.1 Pennsylvania's Energy Market

This section examines the impacts of climate change on the energy sector in Pennsylvania. It also explores opportunities and barriers to realizing them, of the need for alternative energy sources, climate-related technologies, services, and strategies, carbon sequestration technologies, capture and utilization of greenhouse gas emissions, and other mitigation strategies.

Pennsylvania is a major energy-producing state. It ranks third in the nation in electric power production, fourth in the nation in coal production, 15th in the nation in natural gas production and 19th in the nation in crude-oil extraction (EIA, 2008).[9] Overall, the Commonwealth is an energy importer – total energy production in 2006 amounted to 2.6 quadrillion BTU[10] while total energy consumption for all purposes in 2006 was 3.9 quadrillion BTU. These aggregate figures mask some differences in the Commonwealth's demand-supply balance for specific energy sources. While Pennsylvania is currently a net importer of crude oil, for example, the Commonwealth is one of the largest exporters of electric power in the U.S. Approximately 30 percent of the electricity produced in the Commonwealth is exported to other states. Pennsylvania is also a major coal exporter; approximately one-half of the coal extracted in Pennsylvania is sold to other states. Pennsylvania is also the largest producer of refined petroleum products in the Northeastern U.S.

Energy prices in Pennsylvania are generally at levels close to the national average. As of November 2008, the price of regular gasoline averaged $1.68 per gallon in the Commonwealth, or 6 percent above the national average. Residential and industrial electric customers pay 11.38 cents/kWh and 7.01 cents/kWh, both slightly below the national average. Commercial customers in Pennsylvania pay prices well below the national average; 9.43 cents per kWh versus 10.13 cents per kWh for the U.S. as a whole. Delivered natural gas prices in Pennsylvania are generally higher than the national average, at $18.02/mcf. The Commonwealth does not currently produce very much gas within the state, so Pennsylvania is dependent on a number of major pipelines to transport gas from major producers in the U.S. Gulf. These pipelines currently carry approximately 10,000 mmcf of natural gas per day through Pennsylvania. The natural gas supply picture in Pennsylvania, however, is undergoing a number of changes. Development of the Marcellus Shale gas formation represents a major potential supply source for both Pennsylvania and the U.S. Northeast. Planned pipeline and LNG projects could bring additional natural gas supplies to Pennsylvania from the U.S. Rocky Mountain region and the eastern seaboard.

Coal and nuclear power are the predominant fuels used for generating electricity in Pennsylvania. Pennsylvania's installed capacity mix (as of 2006) is shown in Figure 10.1, while utilization of fuels for electric generation is shown in Figure 10.2.

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[9] Figures for natural gas do not include Marcellus Shale development.
[10] One quadrillion BTU (British Thermal Units) is commonly referred to as a "quad."

Pennsylvania's capacity mix is similar to the mix of the U.S. as a whole. The cost of fuels, capital and maintenance all influence how often generating units are used. There is thus a substantial difference between Pennsylvania's installed capacity and which generating units or technologies are used most intensively to generate electricity.

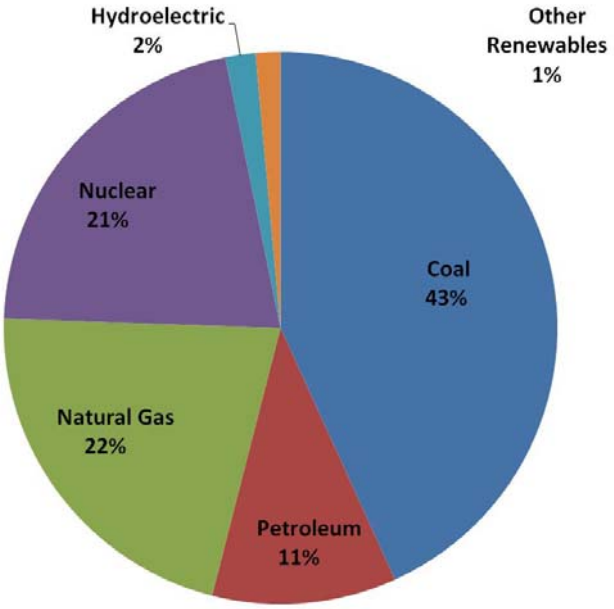


Figure 10.1. Installed capacity mix for electric generation in Pennsylvania

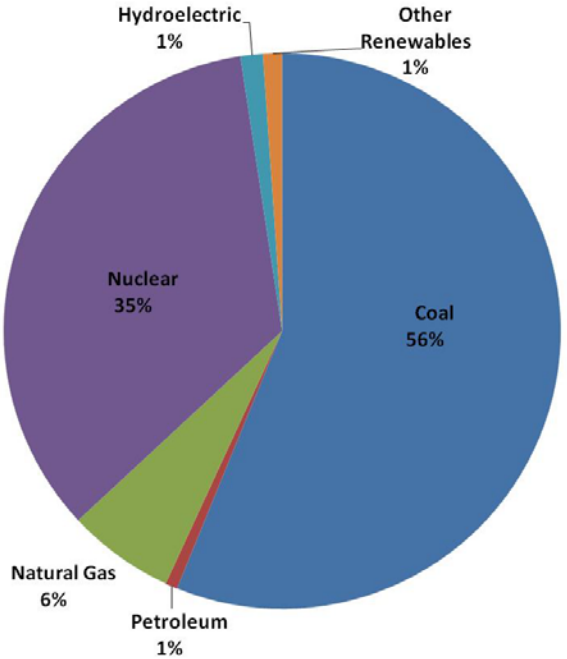


Figure 10.2. Fuel mix for electric production in Pennsylvania, based on 2006 production.

10.1.1 Energy Consumption in Pennsylvania

Total energy consumption over all sectors and for all uses in Pennsylvania was 3.9 quadrillion BTU in 2006. Figure 10.3 shows a breakdown of total energy consumption in Pennsylvania by sector, based on 2006 data. The industrial and transportation sectors consumed the largest amount of total energy.

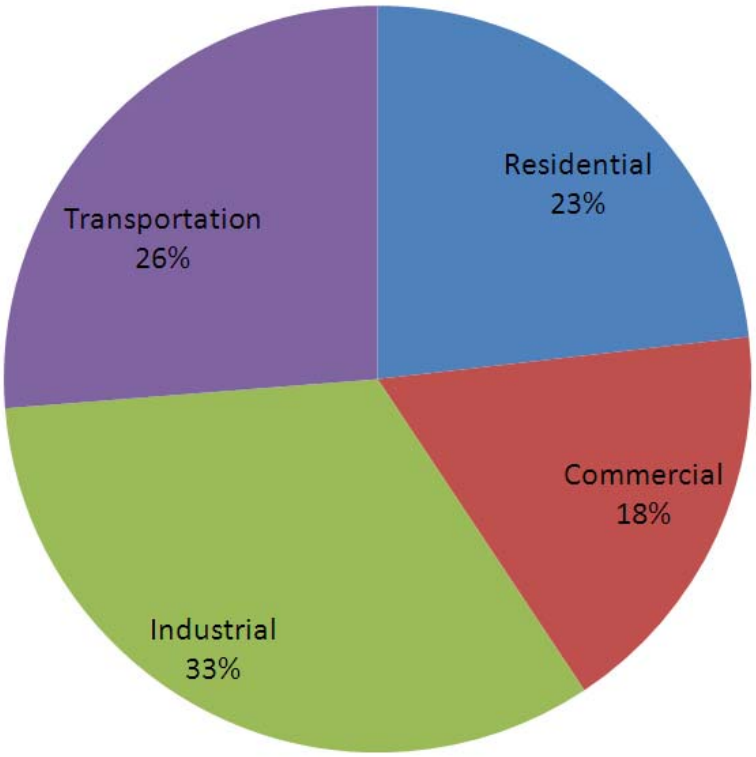


Figure 10.3. Sectoral energy consumption in Pennsylvania, 2006. Total energy consumption in the Commonwealth was 3.9 quads.

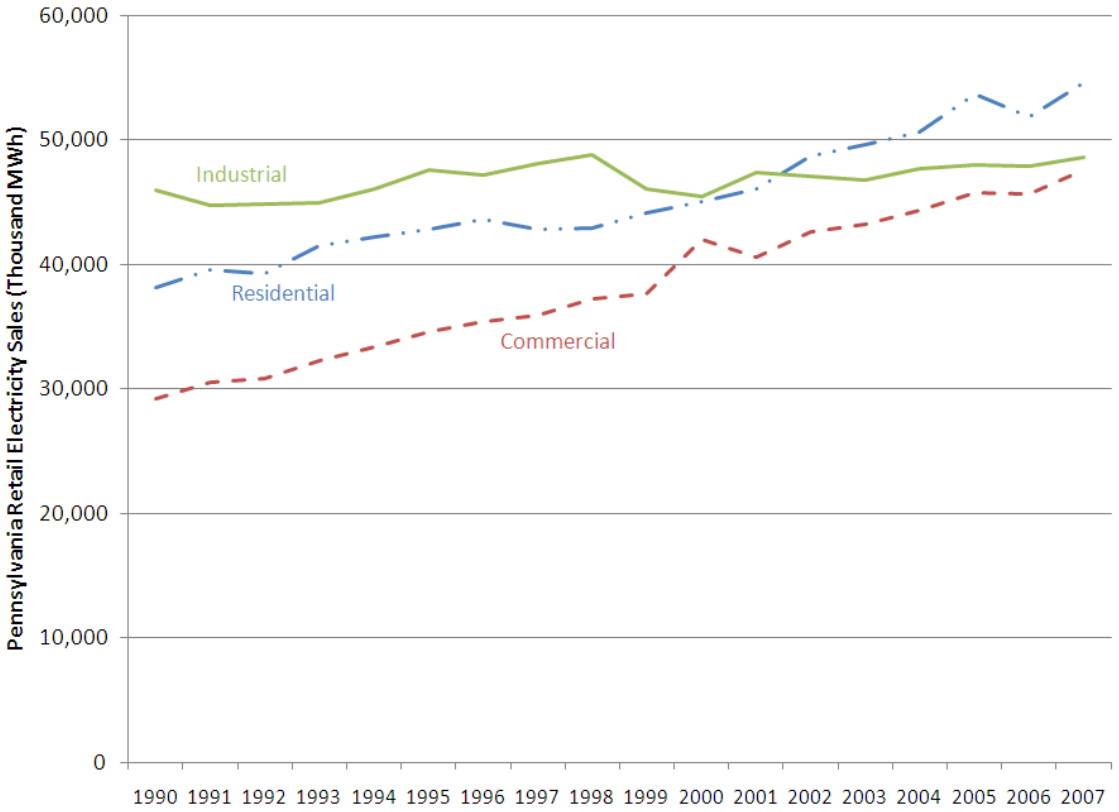


Figure 10.4. Annual electric sales to residential, commercial and industrial customers in Pennsylvania, 1990 – 2007.

Electricity demand in Pennsylvania varies by the time of day and by months in a year. Annually, Pennsylvania sees its peak electricity demand during the summer months, as shown in Figure 10.5. The Commonwealth also has a smaller winter peak, typically in January or February. The lighter-load months during the fall and spring are often referred to as the "shoulder period." The summer peak in electricity demand is generally driven by electric air conditioning. Electric heating represents a significant electric load in the Commonwealth during the wintertime, even though relatively few consumers use electricity for heating. Most households in Pennsylvania use natural gas for heat (51 percent) or fuel oil (26 percent). Only 17 percent of households in Pennsylvania use electricity directly for heating. Three percent of households in Pennsylvania use propane or bottled gas for heating, while another three percent use other heating sources or do not heat their homes.

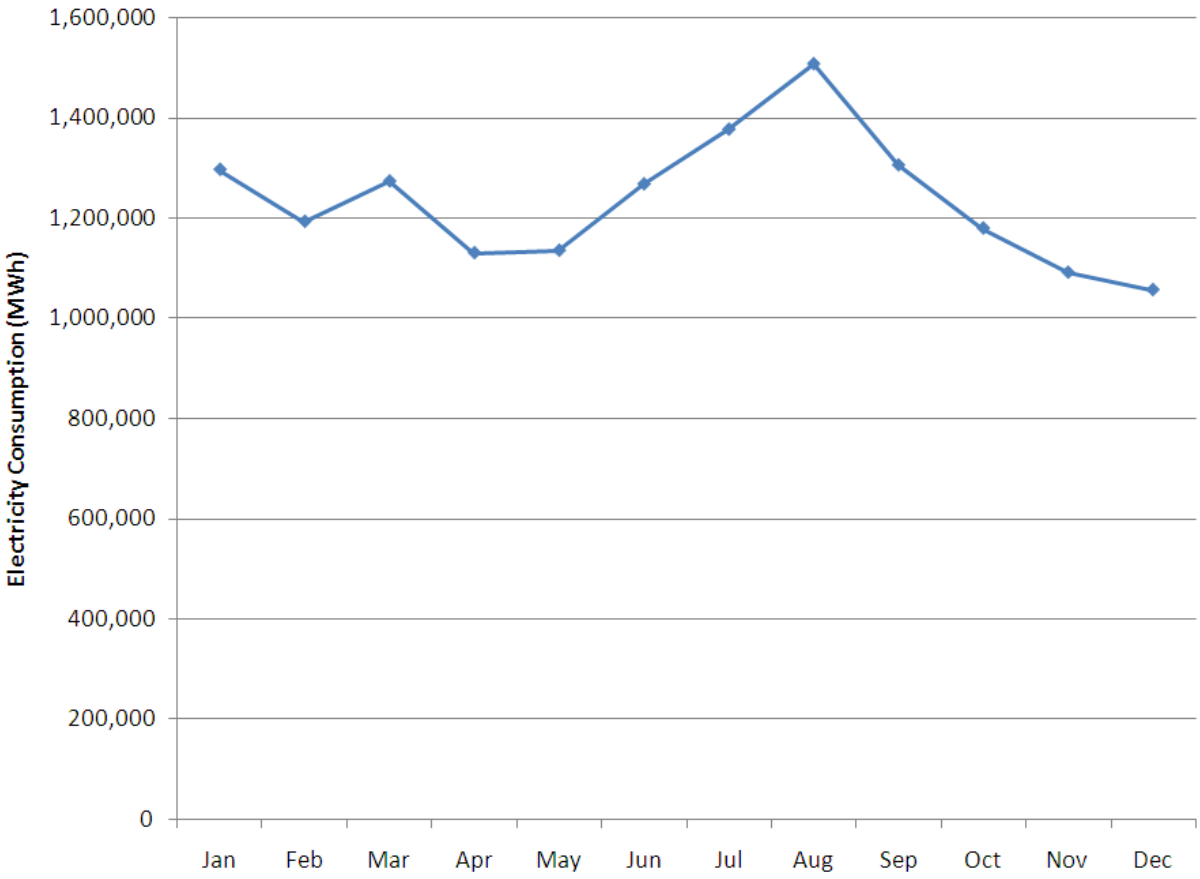


Figure 10.5. Monthly electricity consumption for Pennsylvania in 2006, all sectors.

Pennsylvania lies in the footprint of three Regional Transmission Organizations (RTOs). An RTO manages the transmission grid within its footprint to ensure electric reliability, performs regional planning, and operates spot markets for electric energy (as well as capacity and transmission rights, in some cases). Most of Pennsylvania lies in the footprint of the PJM Interconnection, whose territory covers all or part of thirteen states, as illustrated in Figure 10.6. Penn Power, in Western Pennsylvania, is part of the Midwest ISO. Pike County Power and Light, in Northeastern Pennsylvania, is part of the New York ISO. RTOs perform a joint regional dispatch of power plants within their footprint. Thus, Pennsylvania's electricity market is highly integrated with markets in a number of other states. Demand and supply conditions in one portion of a RTO market can impact wholesale generation prices in other portions of the RTO territory. Geographic price differences within RTOs are generally caused by congestion on the high-voltage transmission network. Figure 10.7 shows a contour map of PJM market prices on a warm (but not unusually hot) summer day. The effect of transmission constraints between western and eastern Pennsylvania is apparent.

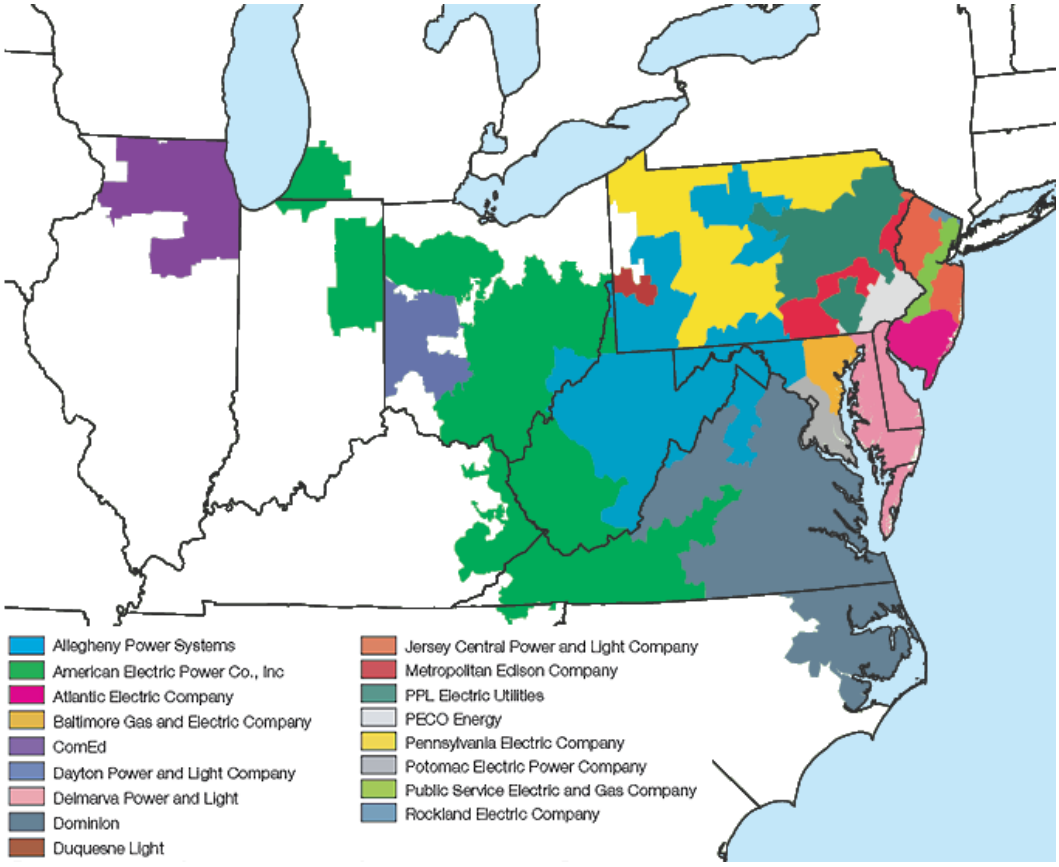


Figure 10.6. Service territory of the PJM Interconnection. Source: PJM.

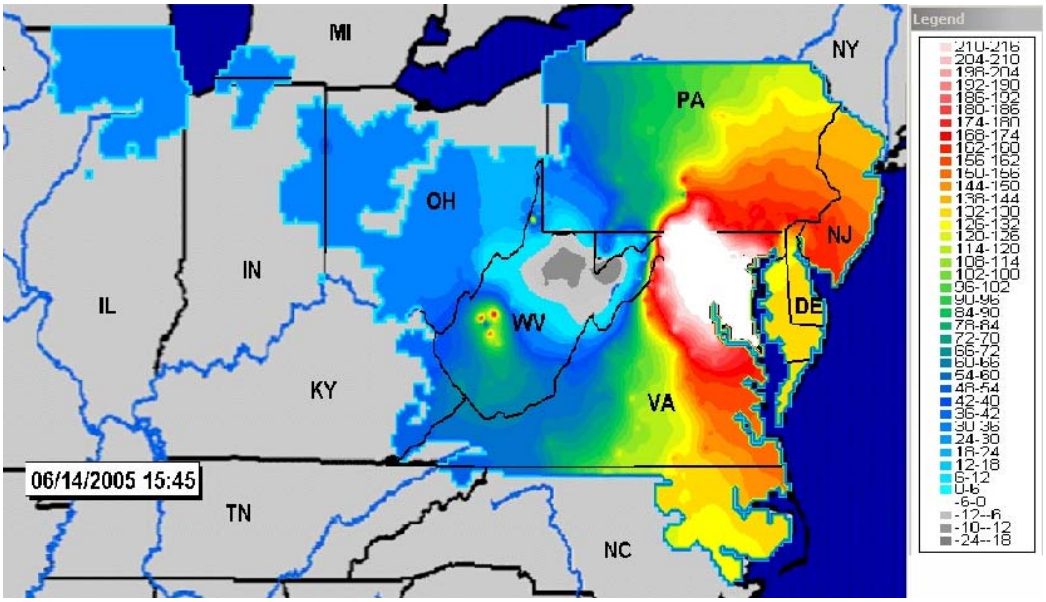


Figure 10.7. Wholesale prices in dollars per MWh in PJM, June 14, 2005 at 3:45 PM. A price in the deep red of $180 per MWh converts to 18 cents per kWh. White represents prices greater than $216. Source: Apt, et al (2007), from PJM eTools.

While overall electricity sales have been growing in Pennsylvania (with the fastest growth in the commercial sector, as shown in Figure 10.4), there is evidence that peak demand has been growing faster than average demand in the PJM electricity market, particularly beginning in 2005 (Figure 10.8). Similar trends have been observed in New England by Spees (2008). The increased "peakiness" of electricity demand presents economic and reliability challenges to utilities and system operators who must invest in peaking power plants to meet this demand. In PJM, these plants are typically simple-cycle gas combustion turbines or diesel engines. These peaking units have low capital costs but are inefficient and run on high-cost fuel, so the variable operating costs of these units are large. Further, using these plants for load-following services means running the plants in an inefficient fashion, resulting in increased emissions of greenhouse gases and some criteria pollutants. Finally, Spees (2008) and Spees and Lave (2008) calculate that 15 percent of the generating capacity in PJM and New England is used less than one percent of all hours in a year. Peaking units thus have high average costs, which must be passed on to electricity consumers.

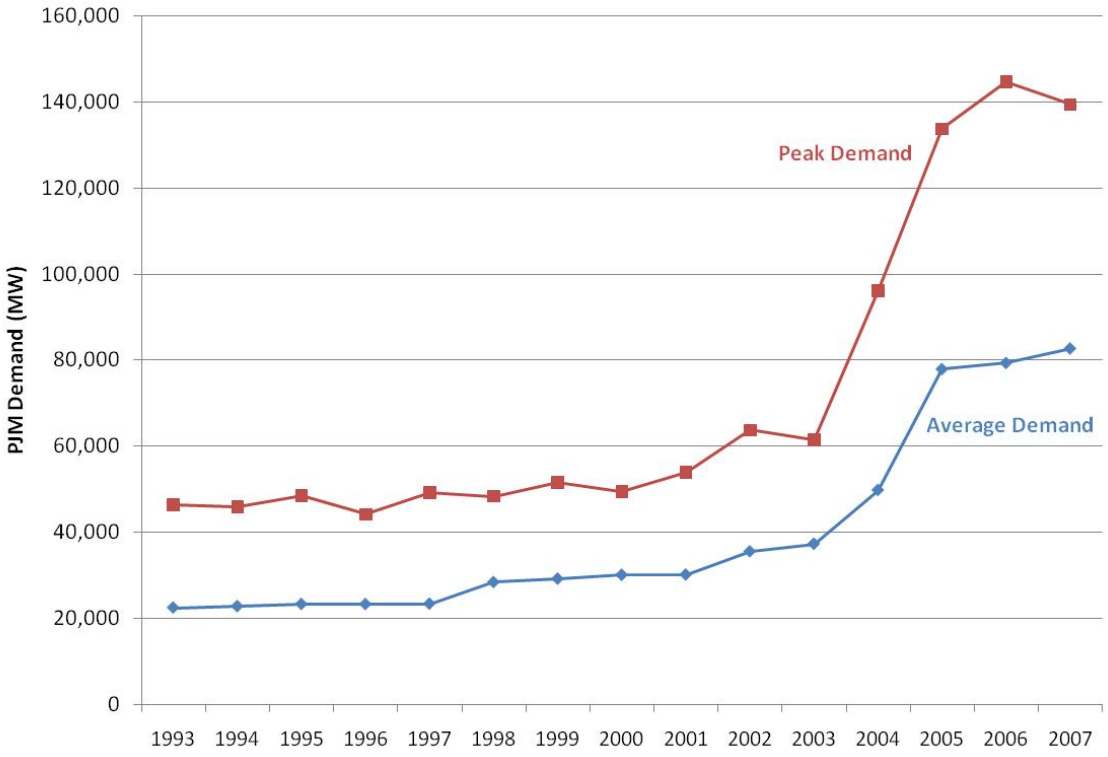


Figure 10.8. Annual peak and average demand in the PJM electricity market, 1993 – 2007. Source: Author calculation from PJM data.

10.2 Greenhouse gas Impacts of Energy Production and Consumption in Pennsylvania

Greenhouse gas emissions related to energy supply and consumption in Pennsylvania are significant. The primary sources of energy-related greenhouse gas emissions are from the electric power, transportation and industrial sectors. The burning of fossil fuels for space conditioning in homes or commercial buildings also contributes, but these effects are small by comparison, particularly since the majority of homes in Pennsylvania use natural gas for heating. Table 10.1 shows average and total carbon dioxide emissions from the burning of fossil fuels for various consumptive uses, including the generation of electricity. The figures for electricity generation are based on data specific to Pennsylvania, from the Emissions and Generation Resource Integrated Database (eGRID) available through the U.S. Environmental Protection Agency.[11] The figures for home heating from fuel oil or natural gas are taken from Blumsack et al. (2009). Pennsylvania's greenhouse gas emissions, by source, are summarized in Figure 10.9.

Table 10.1. Average and annual CO_2 emissions from energy use in Pennsylvania. Annual figures are based on 2005 data.

Source	Average CO2 Emissions (pounds per MegaJoule)	Total for PA, 2005 (tons CO2)
*Electric Generation**		
Coal	0.63	123,371,049
Natural Gas	0.40	5,181,029
Petroleum	0.73	3,782,066
Transportation	0.01	49,806,187
Home Heating		
Natural Gas**	0.11	24,080,121
Heating Oil	0.16	8,057,884

**Electric Generation includes consumption for residential heating and cooling.*
***Natural Gas includes cooking fuel.*

[11] http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.

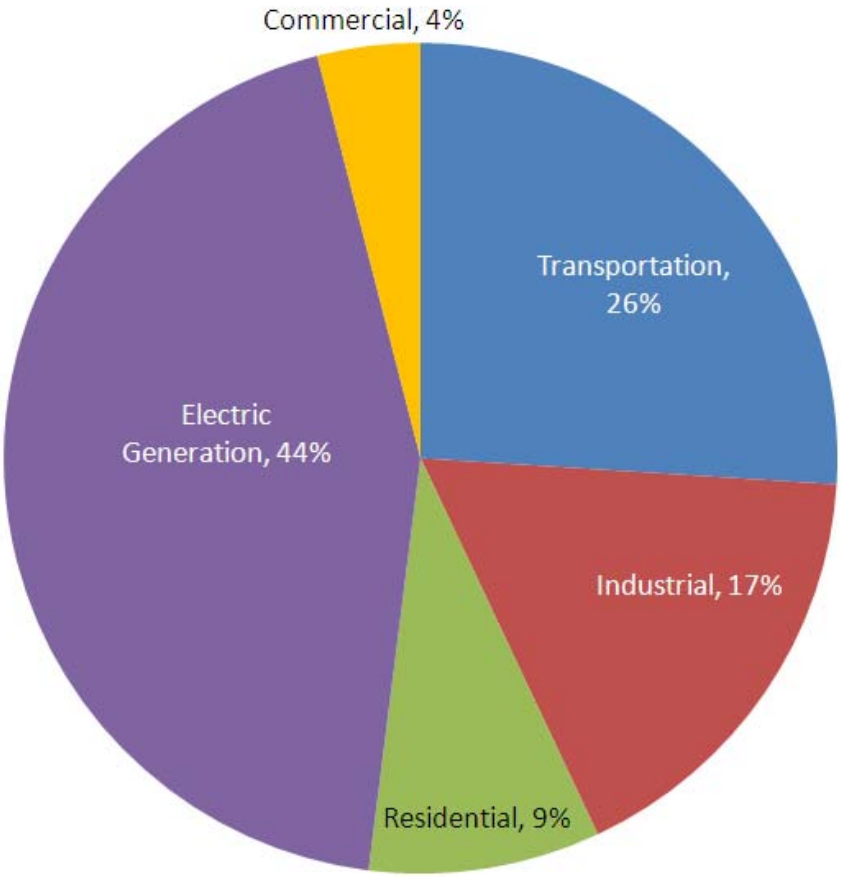


Figure 10.9. Sectoral emissions breakdown for Pennsylvania, 2006.

Pennsylvania's emissions from the electric power sector are dominated by coal-fired generation. As Table 10.1 demonstrates, Pennsylvania's coal plants emit on average more than one ton of CO_2 per megawatt-hour generated, while natural gas emits half as much CO_2. The burning of refined petroleum for electricity is more carbon-intensive than burning coal, but oil-fired generation accounts for only a small portion of the Commonwealth's electric-sector emissions. The emissions figures in Table 10.1 only include emissions from the actual production of electric power. A broader life-cycle emissions picture from electric generation sources is shown in Figure 10.10. These life-cycle environmental impact figures are based on published values from the literature and are not specific to Pennsylvania, and include upstream emissions (from fuel extraction, processing and transport), emissions associated with plant construction, and emissions associated with decommissioning, where appropriate. A life-cycle environmental analysis does not change the fact that coal is the most carbon-intensive fuel source for power generation, but it does illustrate that even "carbon-free" generation does not always imply zero emissions.

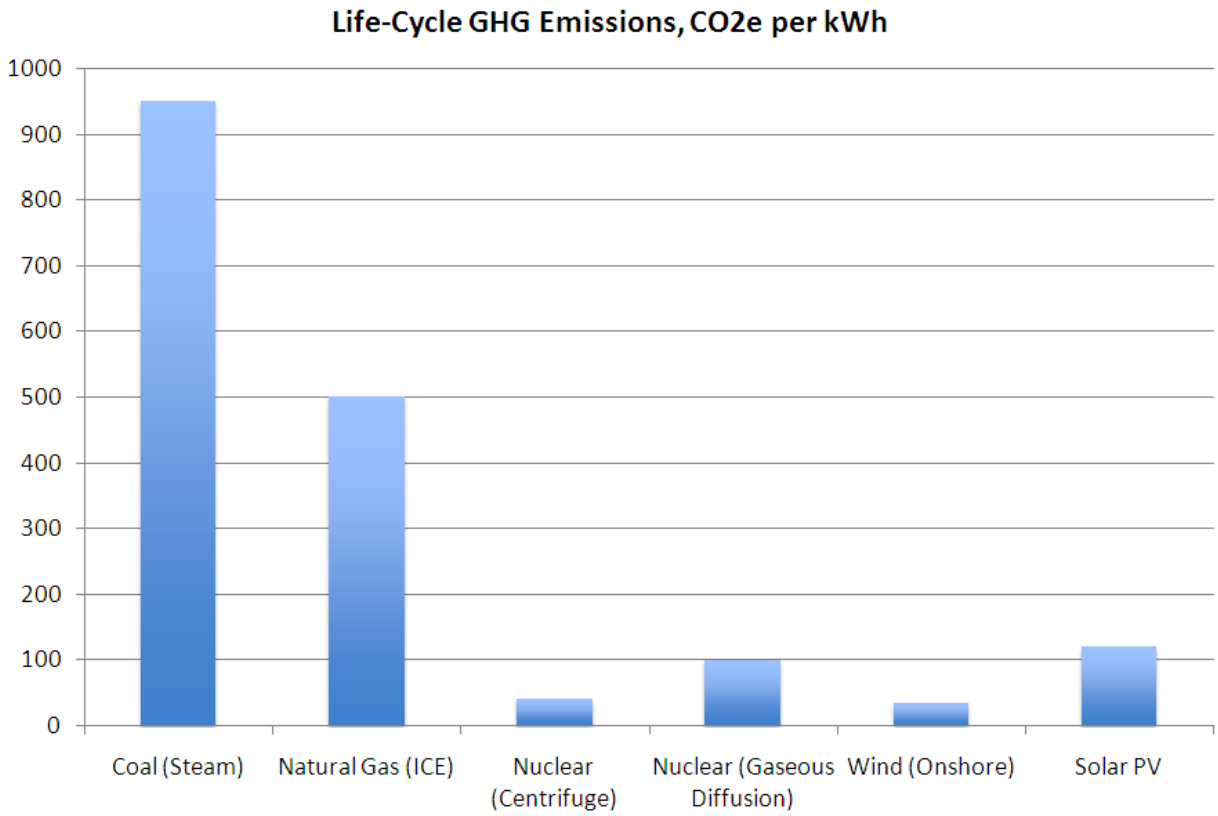


Figure 10.10. Life-cycle emissions factors for different fuels used in the generation of electric power. The figures are drawn from the literature and are not specific to Pennsylvania. Sources: Fthenakis and Kim (2006); Kim and Dale (2005); van Leuween (1995).

10.3 Energy Use Scenarios Under Climate Change

The primary longer-term determinants of energy use are population growth, wealth and overall economic activity. Weather is usually considered a cyclical or shorter-term factor in energy demand – overall energy demand is higher during the winter and summer (for heating and cooling) than during the spring and fall. Some components of overall energy demand, such as transportation, show less seasonal variation. The potential for a warming of Pennsylvania's climate during the 21st century implies that weather or climate considerations may play a larger longer-term role in influencing energy demand.

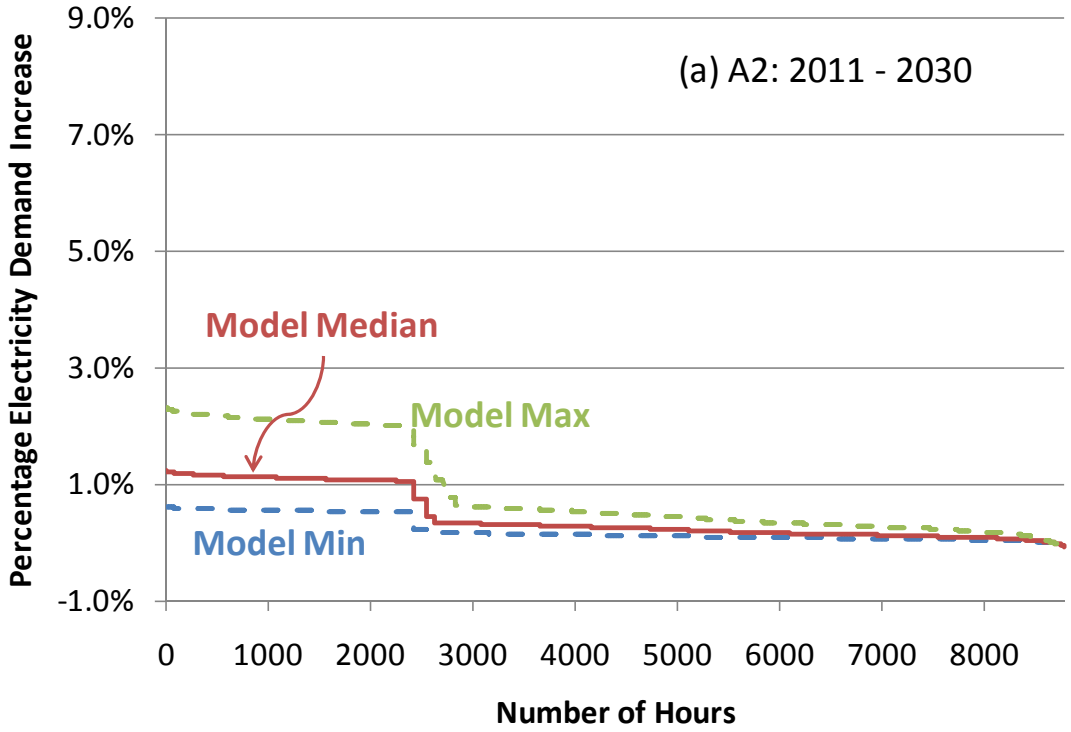
10.3.1 Electricity Demand Under Climate Change

Overall electricity growth has grown linearly over the past 20 years with the average annual growth in electric sales equal to approximately two million megawatt-hours per year (see Figure 10.4). The average growth rate over that same period has been 2 percent annually, but we again emphasize that electricity demand growth in the Commonwealth has been linear, rather than exponential. PJM has estimated that over 500 MW of new

generating capacity will be required annually to meet Pennsylvania's growing electricity demand (PJM, 2007).

Whether climate change in Pennsylvania will itself increase electricity demand is uncertain. Rising summer temperatures will lead to increased use of air conditioning, and increased demand for air conditioning in both new and existing buildings. On the other hand, electricity demand for heating in the winter months will decline, for those Pennsylvania electricity consumers that use electricity for space heating. Since most Pennsylvanians use an energy source other than electricity for heating, the increase in air conditioning demand would likely outweigh the decrease in electric-heating demand, in terms of kilowatt-hours consumed. In the absence of significant behavioral changes on the part of electricity consumers, or effective policies to reduce electricity demand, future warming in Pennsylvania is highly certain to increase electricity demand to some degree. Figures 10.11 (a) – (f) show the output of a model relating electricity demand in Pennsylvania to warming in Pennsylvania. The model uses the projections for warming in Pennsylvania discussed in Section 4.4.2. The model is described in more detail in Appendix 7, but we emphasize here that the model captures only on that element of electricity demand influenced by warming in Pennsylvania. Behavioral changes in electricity demand and increased energy efficiency, for example, are not considered in this particular model.

For each climate scenario, we use the maximum, minimum and median seasonal warming from the climate model output shown in Section 4.4.2, and we apply those temperature differences to hourly average temperatures for Pennsylvania for 2007. Changes in temperature (translated into changes into heating degree days and cooling degree days, as discussed further in Appendix 7) were mapped into changes in overall electricity demand using a simple regression model. Figure 10.11 suggests that in the absence of changes in consumer behavior or significant energy efficiency advances, summer peaks in Pennsylvania territory are virtually certain to become more pronounced, and that increased cooling demand is virtually certain to more than offset decreases in electric heating demand. Changes in the total estimated amount of electricity demanded during the course of a year, relative to the 2007 base case, are shown in Figure 10.12.



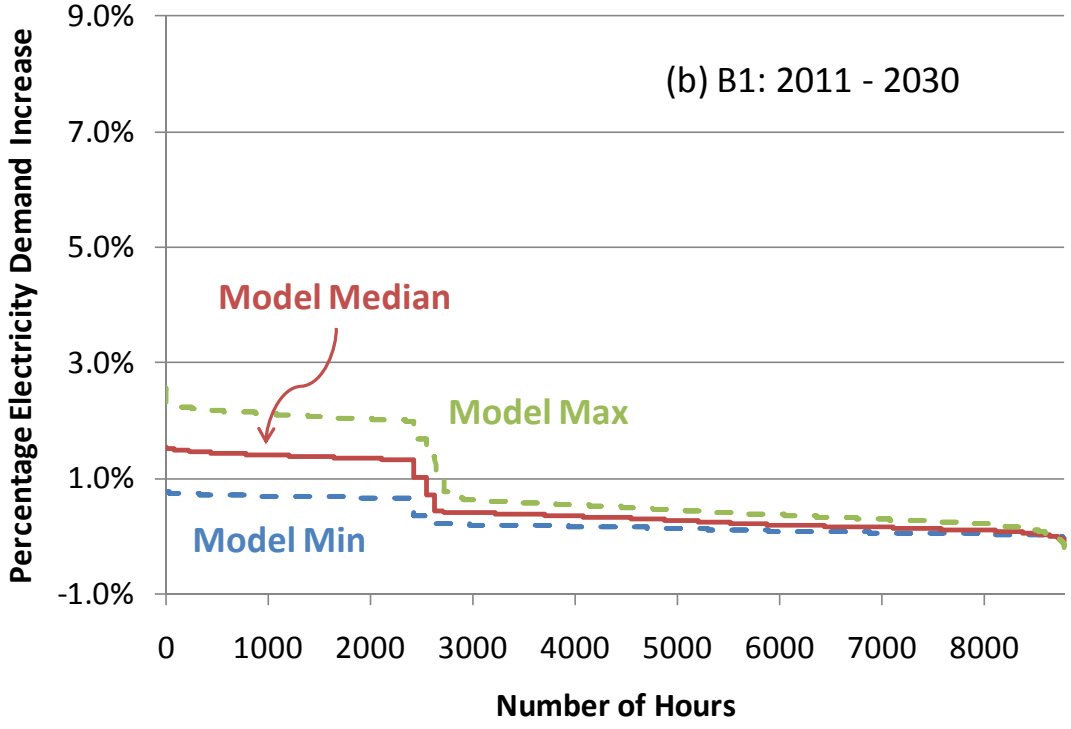
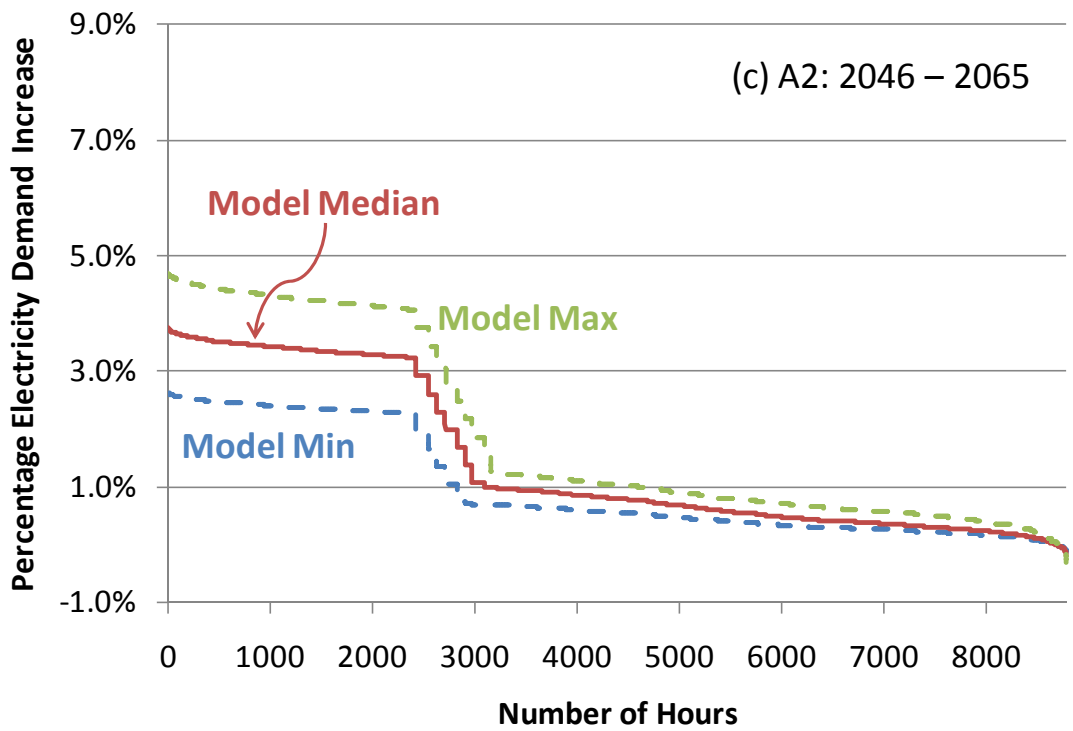


Figure 10.11(a)-(b)



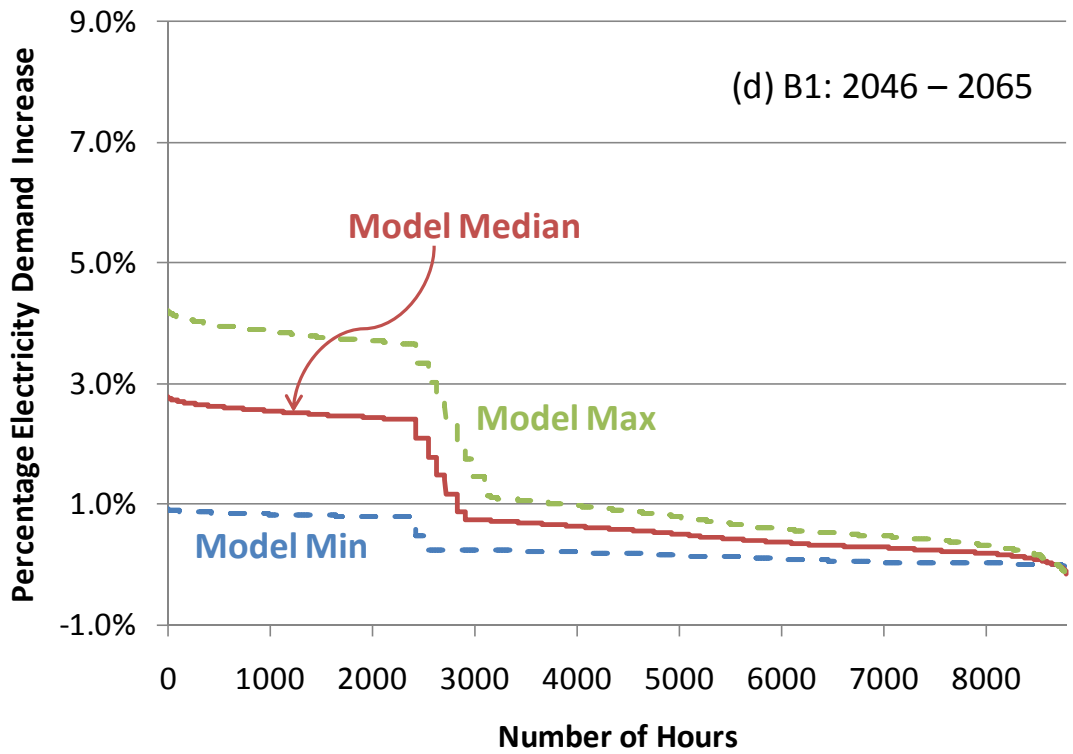
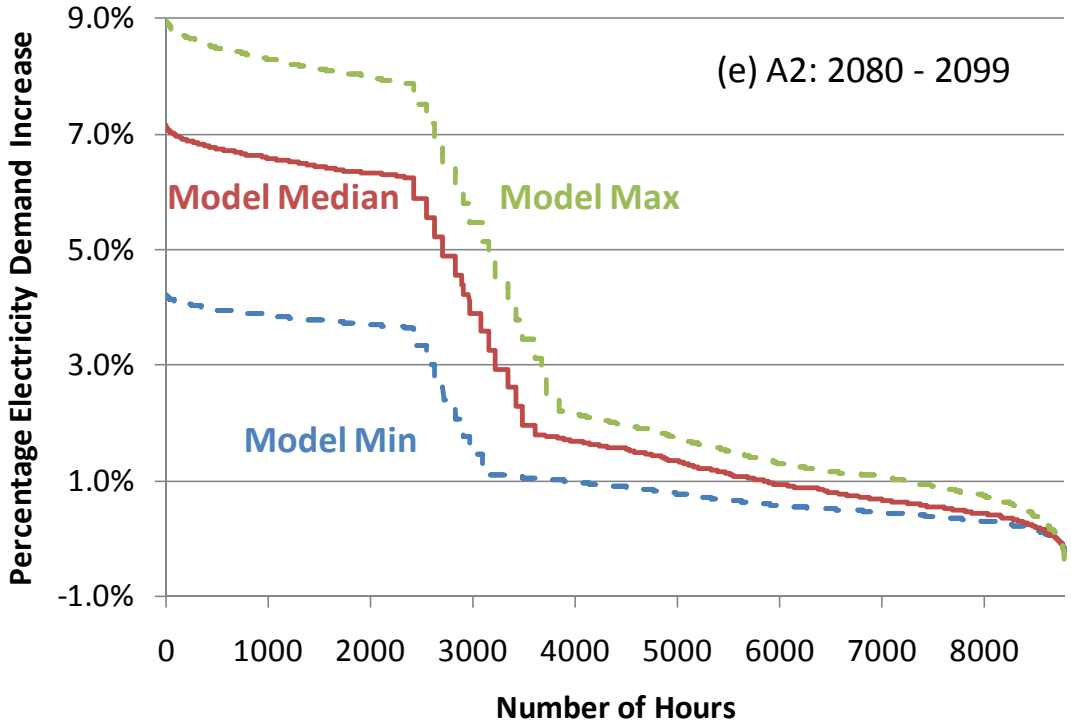


Figure 10.11(c)-(d)



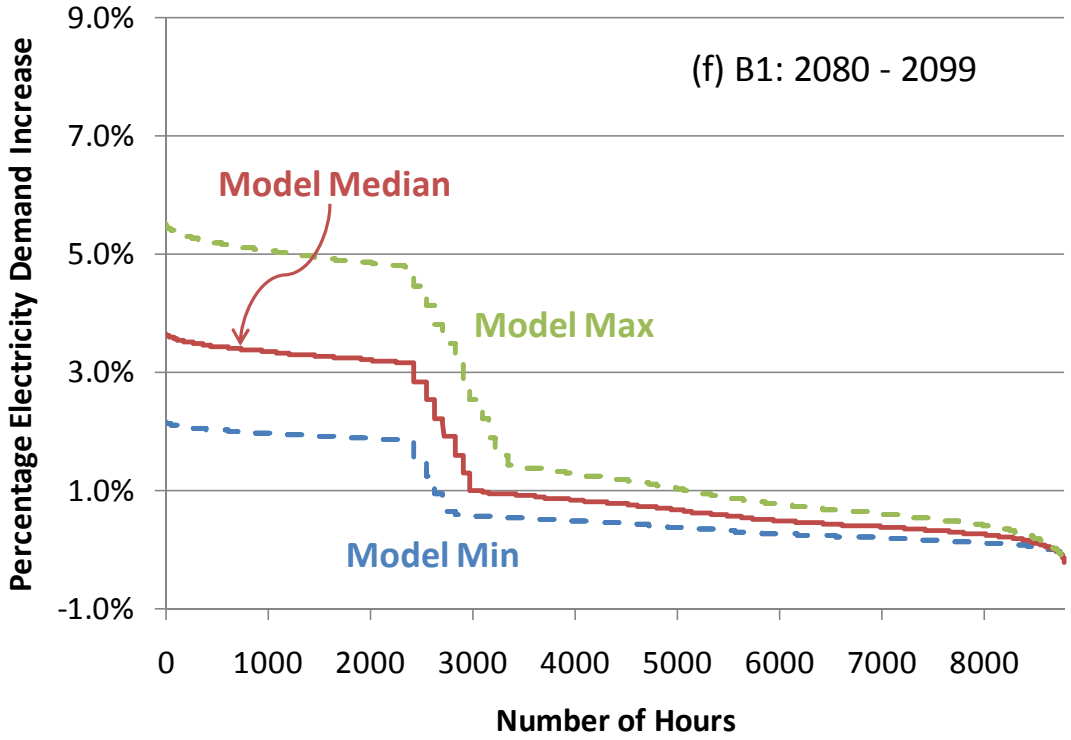


Figure 10.11(e)-(f). Estimated changes in Pennsylvania electricity demand under two future climate scenarios, for three future periods. The solid line represents the median climate model warming output; the dotted lines represent the maximum and minimum climate model outputs.

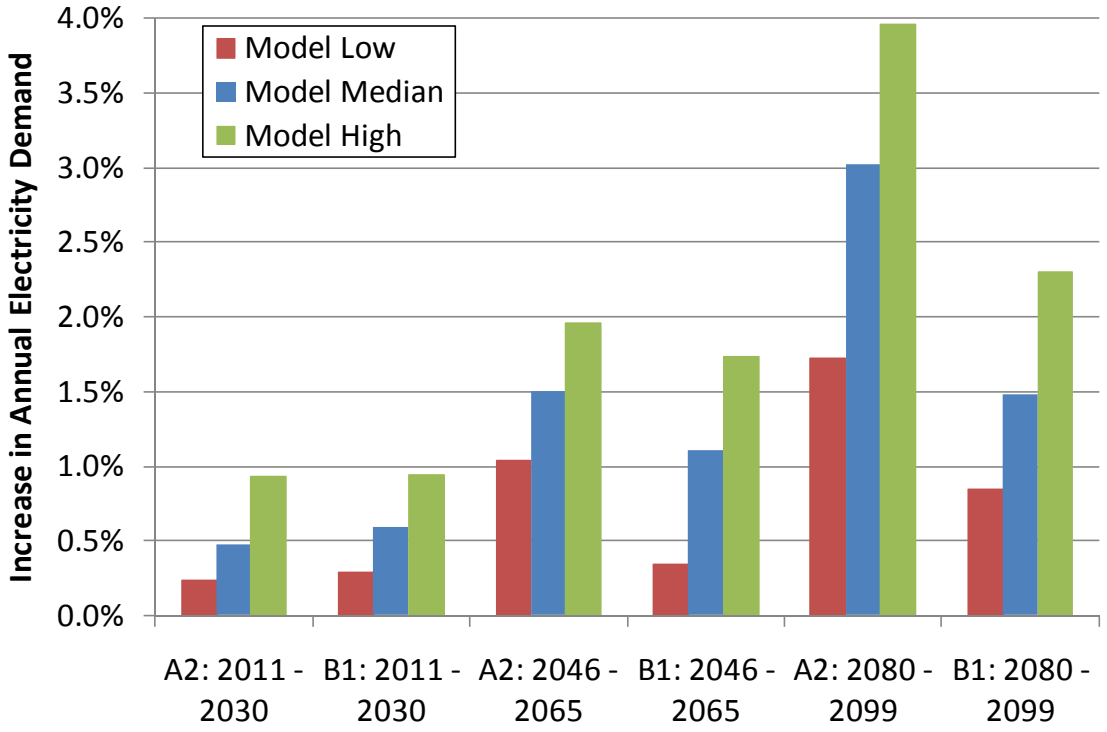


Figure 10.12. Total annual increase in Pennsylvania electricity demand under two climate scenarios, for three future periods.

10.3.2 The Effect of Climate Policy on Power Plant Utilization and Investment

Placing an explicit price on greenhouse gas emissions, either through the imposition of a tax or the establishment of a cap-and-trade system, is one policy response to address climate change. The immediate effect of placing a price on greenhouse gas emissions from power plants will be to increase the costs of plants with high per-unit emissions factors. If greenhouse gas pricing is implemented in tandem with the real-time pricing of electricity for all customers, and if consumers have the means to observe and respond to changing hourly electricity prices, then economists expect that the demand for electricity will decrease when costs for power generation increase. Thus, there are two possible pathways by which greenhouse gas emissions could decrease in the short run (before any new power plants could be built or before consumers could engage in significant energy-efficiency measures):

1. The imposition of a carbon price will increase the cost of coal-fired power generation, relative to natural gas or other forms of generation. Since PJM dispatches power plants in least-cost order, PJM may substitute natural gas generation for coal generation (coal units get dispatched less often due to their increased costs).
2. Consumers will demand less electricity overall.

The effects of pricing greenhouse gas emissions on electricity prices have been studied for regional electricity markets in the Northeastern U.S., and the impacts of carbon

pricing vary from region to region. Carbon pricing through the Northeastern Regional Greenhouse Gas Initiative (RGGI) has been predicted to have little effect on electricity prices (Ruth, et al., 2008), though in this case the pricing of carbon dioxide is assumed to go hand-in-hand with aggressive demand reduction. Studies of the PJM market (Newcomer, et al., 2008; Blumsack, 2009) concludes that a carbon price of $50 per metric ton of CO_2 (the amount at which advanced coal gasification technologies are thought to become cost-competitive), the average cost of electricity in the PJM market will increase by over 30 percent, with the largest percentage price increases observed during peak hours. Emissions of greenhouse gases in the PJM territory, meanwhile, could decline by between 10 percent to 15 percent. This decline in emissions happens in the short run, i.e., before utilities can make any new investments in low-emissions generation technologies. Greenhouse gas emissions in PJM decrease almost entirely due to decreased demand for electricity. The study observed very little substitution of natural gas power for coal power, as shown in Table 10.2 and Figure 10.13. Although natural gas power plants emit approximately one-half of the greenhouse gases as coal-fired power plants, the price differences between fuels are sufficiently large (approximately $2 per mmBTU for coal versus $7 per mmBTU for natural gas) that even with a relatively large carbon tax, coal-fired power is still cheaper than lower-emissions alternatives in the short run. A carbon tax of approximately $80 per metric ton of CO_2 would be required before natural gas would begin to displace coal in the dispatch order.

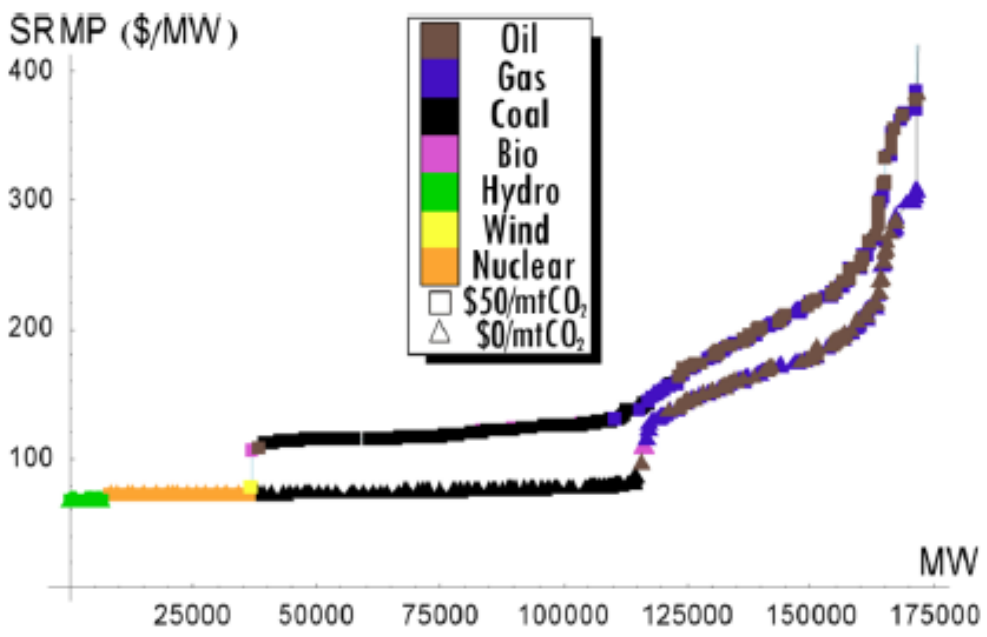


Figure 10.13. The dispatch curve for the PJM system with zero carbon tax and a tax of $50 per metric ton of CO_2. Source: Newcomer, et al. (2008)

CO2 Price ($/tonne)	**% Change in Fuel Use**	
	Coal	*Natural Gas*
20	-5.2	-4.9
35	-10.1	-11.6
50	-15.4	-14.4

Table 10.2. Change in coal and natural gas utilization with a price on carbon in PJM. Source: Newcomer et al. (2008)

Models predict that a price on greenhouse gas emissions will likely lead to some amount of greenhouse gas reductions in the short run, but these reductions arise almost entirely from a reduction in electricity demand. Pricing carbon in and of itself is unlikely to, in the short run, lead to lower-emission fuels displacing coal for electricity generation. Some fossil plants may find that the imposition of a carbon tax shrinks their profit margins to the point where they can no longer recover "going-forward" costs (fixed operations and maintenance costs, for example) and must effectively offer their generation into the PJM market at higher prices or withdraw from the market, leading to some degree of short-run natural gas substitution in the dispatch order. Existing studies do not consider this possibility, since detailed cost data for fossil plants is not publicly available. Without this detailed cost information, it is thus impossible to accurately assess the likelihood of a carbon tax placing fossil plants in a position where costs cannot be fully recovered.

In the long run, a price on greenhouse gas may alter the investment decisions of electric generation companies. Some evidence of a shift towards natural gas generation and away from coal for base-load generation exists, due in part to factors related to electricity deregulation and in part to uncertainty over future environmental regulations. The generation interconnection queue for PJM shows that approximately two-thirds of proposed new power plants in Pennsylvania will be fueled by natural gas. Most existing coal plants are between 20 and 50 years old. Even with extensive upgrades and retrofits, these plants cannot run forever. With some sort of price placed on CO_2 emissions, retrofitting old coal plants is likely to become less profitable (Patino et al., 2007).

Newcomer (2008) models investments in new generation in PJM under a number of scenarios where investors choose not to build new coal plants in response to growth in electricity demand, or where the use of coal for electricity generation has been effectively prohibited. The scenarios modeled include a large investment in renewables such as wind power (consistent with the DOE's 20 percent by 2030 scenario); aggressive demand reductions; and a large build-out in natural gas generating capacity. Compared to a "business as usual" scenario consistent with Energy Information Administration Scenarios through 2030, under the wind scenario or the gas build-out scenario, natural gas becomes the dominant fuel setting market prices in PJM.[12] Currently, prices in PJM are set by a mix of coal, natural gas, and (during very light-load periods) nuclear power.

[12] The "system marginal price" in PJM is determined by the marginal cost of the last generating unit dispatched to meet required electricity demand.

Under the scenario with aggressive (and successful) demand response, natural gas does not play as active a role in determining electricity prices. Accordingly, CO_2 emissions from the electric power sector increase considerably – by more than 50 percent - through 2030 under the wind scenario or the gas build-out scenario. The only scenario in Newcomer's model that is able to limit the long-run growth of CO_2 emissions from electricity generation is aggressive demand response and energy efficiency.

10.3.3. Greenhouse Gas Mitigation and Energy Prices

Supply-side policies aimed at mitigating greenhouse gas emissions from the energy sector, such as carbon taxes, cap-and-trade, or portfolio standards, are very likely to increase energy costs from fossil-fuel sources in the short run. Simulations of carbon pricing in the PJM electricity market suggest that a carbon price of between $35 and $50 per metric ton could double the cost of coal-fired electricity and could increase average electric rates in PJM by 30 percent or more. A similar carbon price applied to motor fuel would increase the price of gasoline by approximately 50 cents per gallon. Fuels used for heating buildings would also increase in cost. Models of energy markets that include or assume a significant amount of demand-side response in the form of demand reduction or energy efficiency (such as the study by Ruth, et al., 2008 examining the RGGI carbon market, or Walawalkar et al., 2008 focusing on the PJM electricity market), conclude that demand-side measures can significantly mitigate increases in energy prices due to climate mitigation.

The broader economic impacts of greenhouse gas mitigation have been modeled at the national and global level in a number of studies. Economic impacts are generally sensitive to the magnitude of the mitigation scenario being modeled. A range of models summarized by the U.S. Climate Change Science Program (U.S. CCS, 2007) suggests that less aggressive mitigation policies would reduce annual global GDP by 0.5 percent or less by the end of the 21st Century, while highly aggressive mitigation would reduce annual global GDP between 2 percent and 8 percent by mid-century. Analysis by the Environmental Protection Agency of the Waxman-Markey American Clean Energy and Security Act of 2009 suggests that the mitigation contained in the proposed bill would reduce U.S. GDP (compared to a reference projection) between 0.2 percent and 0.4 percent by 2030. A similar EPA analysis of the Lieberman-Warner Climate Security Act of 2007 (considered more aggressive than Waxman-Markey due to higher emissions permit prices) produced a reduction in U.S. GDP by 0.3 percent to 0.9 percent in the same time period.

Greenhouse gas mitigation policy is highly likely to impact some industries and energy consumers more than others, particularly in the short term. Analysis of the U.S. manufacturing sector by Aldy and Pizer (2009) suggest that a modest CO_2 price of $15 per metric ton would not have a significant impact on U.S. GDP or manufacturing output, though some sectors such as steel, aluminum and paper would see output decrease by approximately 2 percent to 3.4 percent. They note that a significant portion of the decline in manufacturing output is due to decreased demand (due to higher prices for finished

goods) or a shift to manufacturing goods that are less energy-intensive, rather than increased imports or movement of manufacturing operations overseas.

10.3.3 The Impact of Climate on Fuels for Heating and Cooling of Buildings

Electricity is generally the only energy source used for cooling, particularly at the residential level, though there are a variety of electricity-dependent technologies available, aside from electric compressors. The use of ice or deep-water thermal for cooling commercial spaces is beginning to gain in popularity, but even these systems depend on electricity to some degree (electricity is required to make the ice, for example). A variety of different fuels are used for space heating, the most common of which in Pennsylvania are natural gas, fuel oil and electricity (see Table 10.1).

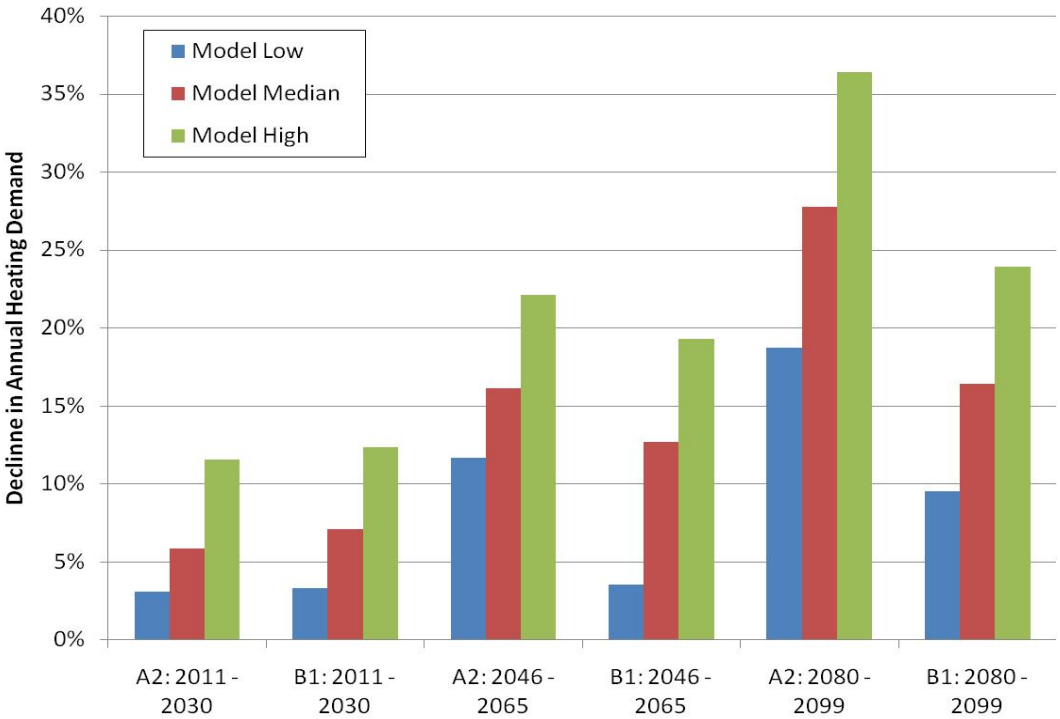


Figure 10.14. Proportional decline in household heating demand, relative to a base case using 2007 temperatures.

Space conditioning represents perhaps the most direct impact of climate change on energy use in Pennsylvania. All of the climate models considered in Section 4 of this report suggest that some amount of warming is virtually certain for Pennsylvania. The climate models thus point towards an increase in the demand for cooling in the summer and a decline in the demand for heating in the winter; this is consistent with other impact assessments for Pennsylvania (Union of Concerned Scientists 2008, Shorr et al., 2009). We examine the net impact of climate change scenarios on the demand for heating and cooling using the model of space-conditioning demand for a Pennsylvania residence described in Blumsack, et al. (2009). We focus attention on this model due to its direct applicability to Pennsylvania's climate. Figures 10.14 and 10.15 show the decline in heating demand and the increase in cooling demand for two climate scenarios (A2 and

B1) over three time periods (2011 – 2030; 2046 – 2065; and 2080 – 2099). The maximum, minimum and median warming from the 14 climate models described in Section 4.4.2 are used as inputs to the model of heating and cooling demand.

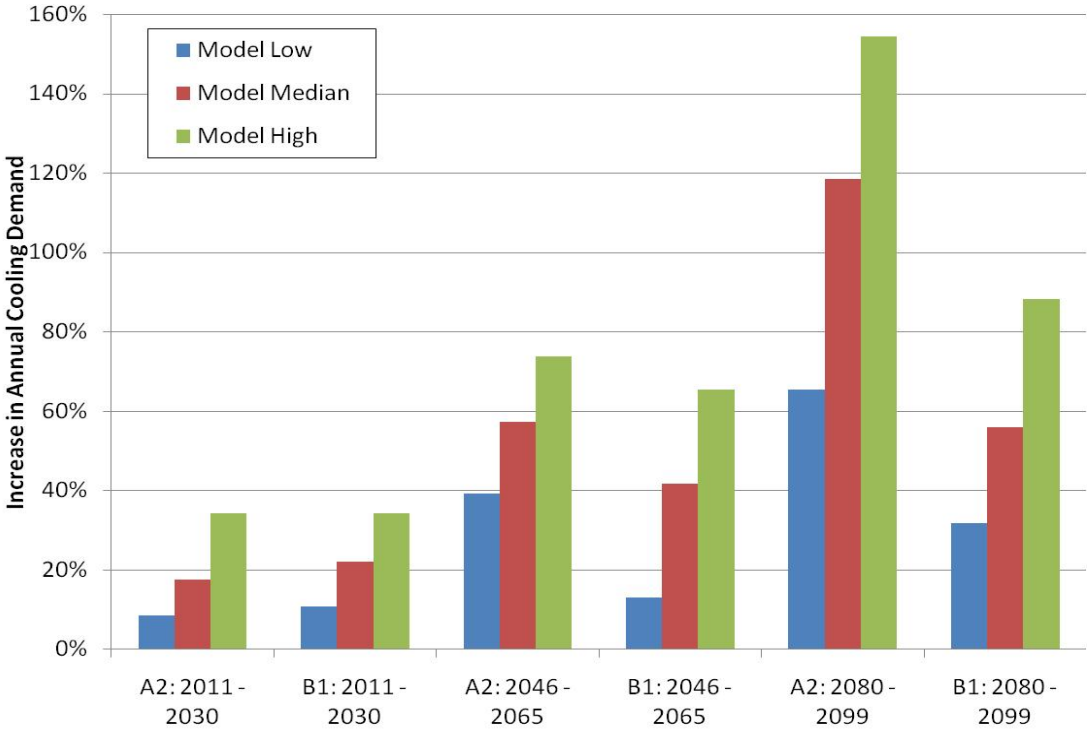


Figure 10.15. Proportional increase in household cooling demand, relative to a base case using 2007 temperatures.

10.3.4 The Impact of Climate on the Demand for Transportation Fuels

Like electricity, the demand for transportation fuels (primarily gasoline and diesel fuel in Pennsylvania) is generally considered to be inelastic with respect to price, at least in the short run. There is some limited evidence of an increase in short-run consumer sensitivity to gasoline prices, based on unusually high gasoline prices during the summer of 2008. The demand for liquid transportation fuels is dependent on population growth, residence patterns (that is, commute distances) and overall economic activity. The most common measure of the demand for transportation fuels is vehicle-miles traveled (VMT). Until the summer of 2008, VMT had been generally increasing over time.

The impact of climate change on the demand for gasoline and diesel fuel will not be direct, since weather is not considered to be a significant factor in the demand for these energy sources. The effects of climate change on vehicle fuels will instead come indirectly, through policy measures aimed at gasoline or overall energy use, or through economic or technological shifts that make other fuels more cost-competitive with gasoline or diesel fuel.

The development of plug-in hybrid electric vehicles (PHEVs) represents one potential shift in the demand for transportation fuels. Since PHEVs emit no greenhouse gases when driven, they are perceived as an attractive solution to environmental as well as energy-security challenges. However, the greenhouse gas impact of PHEVs depends on the fuel source used to charge the car's battery, since emissions are effectively transferred from the tailpipe of the car to the power plant. Samaras and Meisterling (2008), Blumsack et al., (2008) and Stephon and Sullivan (2008) estimate that the life-cycle environmental impacts of PHEVs (including emissions associated with battery production as well as electricity generation) are lower than conventional gasoline-powered vehicles but are approximately even with conventional hybrid vehicles (such as the Toyota Prius). Achieving significant greenhouse gas emissions reductions from PHEVs in Pennsylvania thus involves the same challenges as de-carbonizing the Commonwealth's electric power industry.

10.4 Adaptation and Mitigation Barriers and Opportunities

Adaptation to climate change will largely come in the form of individual responses to changes in weather patterns within Pennsylvania. Homeowners and businesses may increase their use of air conditioning to maintain a comfortable indoor atmosphere during the summer. The increased demand for air conditioning is likely to increase with the number of summer days (particularly consecutive days) surpassing 80 degrees F or 90 degrees F (26 degrees C – 32 degrees C). Individuals and businesses may also make investments in living and working spaces (such as increased insulation, weatherization or more efficient space-conditioning) that will constrain energy use without reducing comfort levels or standards of living. Since energy consumption is a major source of greenhouse gas emissions, many adaptation strategies, particularly when adopted early, will contribute significantly to mitigation of climate change. Separating mitigation from adaptation in the energy realm is thus particularly difficult.

Primarily due to Pennsylvania's position as a large energy producer, the Commonwealth is the third-highest emitter of greenhouse gases in the U.S., and accounts for 1 percent of total global greenhouse gas emissions (Union of Concerned Scientists 2008). Figure 10.10 and Table 10.2 suggest that the largest mitigation opportunities should exist in the power generation and transportation sectors. Significant decarbonization of both sectors will be necessary in order for Pennsylvania to decrease its overall greenhouse gas emissions.

10.4.1 Carbon Sequestration Services

Pennsylvania and other states will continue to rely primarily on fossil fuels for electricity and transportation over the next several decades. Pennsylvania has significant potential for long-term geologic storage of carbon dioxide emissions in formations such as

depleted oil and gas reservoirs, unmineable coal seams,[13] salt caverns, some shales and saline formations. An assessment by the Midwestern Regional Carbon Sequestration Partnership (MRCSP) suggests that the total sequestration potential in Western Pennsylvania alone amounts to 88.5 gigatonnes, or enough to sequester hundreds of years' worth of CO_2 emissions from Pennsylvania's coal-fired power plants. Carbon sequestration thus presents an opportunity for Pennsylvania to reduce its own greenhouse gas emissions, and the Commonwealth could potentially sell emissions-reductions services to other states.

Carbon capture, transport and storage has been utilized in a limited number of applications. There has never been a large-scale commercial demonstration of the feasibility of carbon capture and storage. There are reasonably good expectations that, given an appropriate sequestration formation, that the sequestered CO_2 will stay in place for hundreds of years. Significant uncertainty still exists surrounding the costs of capturing, transporting and storing CO_2 from different sources. The MRCSP has provided some cost estimates for stationary sources, as shown in Figure 10.16. Even more uncertainty exists regarding the feasibility and cost of capturing carbon dioxide from non-stationary sources, such as automobiles.

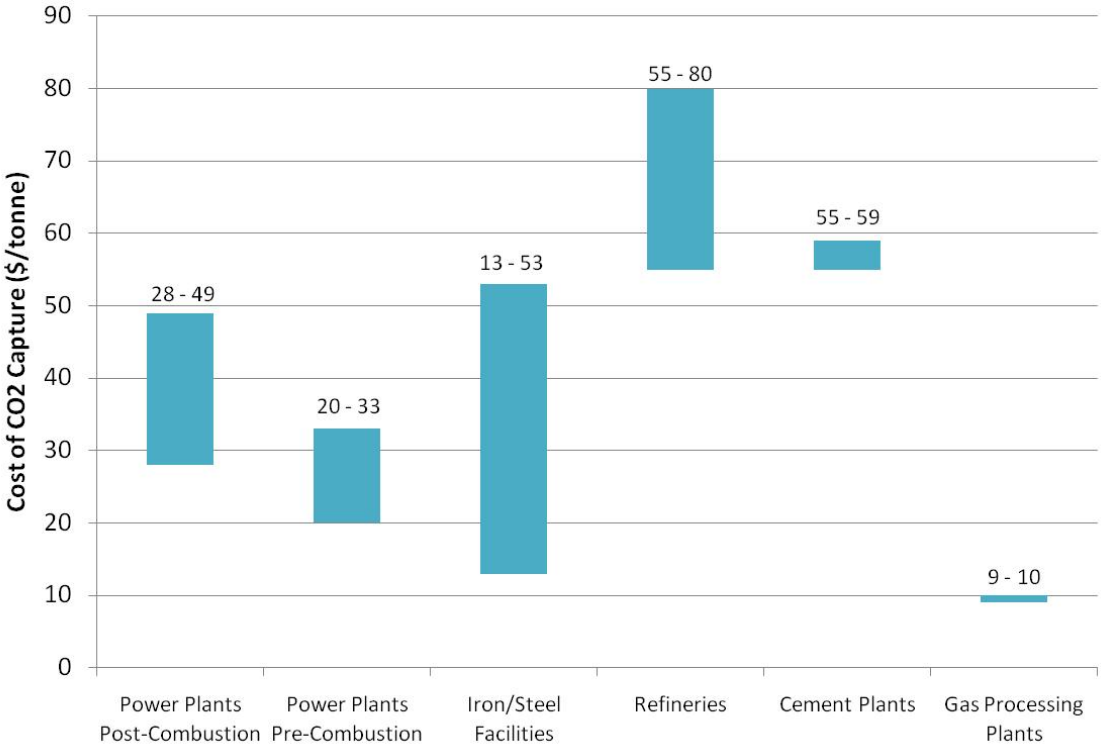


Figure 10.16. Costs of capture for stationary CO_2 sources. Source: MRCSP.

[13] The term "unmineable" is taken to mean coal deposits that cannot be profitably extracted at a reasonable range of market prices. The term should not be taken to suggest that the resources are physically unrecoverable.

10.4.1.1 Barriers to the Development of Carbon Capture and Storage Technologies

A number of legal and regulatory challenges exist in developing Pennsylvania's potential for carbon capture and storage. Further work is needed to resolve these issues before a carbon sequestration industry can emerge in Pennsylvania. Many of these issues are outlined in a recent report from the Department of Conservation and Natural Resources (DCNR 2008). Property rights and liability are two of the most significant issues that will need to be resolved before large-scale sequestration can take place.

An additional barrier to the development of Pennsylvania's carbon sequestration potential is public perception. Studies suggest that while people are willing to bear higher energy costs in exchange for improved environmental quality, and that climate change is a significant global challenge, long-term geologic storage of carbon dioxide is still perceived as a temporary solution that may create future unknown risks and problems (Palmgren, et al., 2004). Further research and education on the actual and perceived risks of geologic carbon sequestration is necessary.

Finally, the DCNR report notes that some of the highest-potential sequestration sites in Pennsylvania are in areas currently being developed for Marcellus Shale production. It is unclear whether the Commonwealth would face tradeoffs between sequestering CO_2 in the Marcellus formation and extracting natural gas from the formation. Similar potential conflicts may exist between gas production, gas storage and CO_2 sequestration. At the very least, it appears that some risk of releasing CO_2 during hydrofracturing might exist. More broadly, whether certain shale formations have a higher value for natural gas development (or storage) or for CO_2 sequestration presents both property-rights and public policy issues. Gas development in one area the Marcellus may, for example, make CO_2 sequestration in the Oriskany formation (which lies below the Marcellus) unacceptably risky. These potential conflicts and social tradeoffs may not be limited to the Marcellus. Further investigation and an explicit cost-benefit study should be undertaken regarding whether conflicts exist between the use of the Marcellus Shale or other shale formations for natural gas production or carbon sequestration, and what the highest-value use of the formation would be.

10.4.2 Barriers and Opportunities in Power Generation

Power generation represents over 40 percent of Pennsylvania's total greenhouse gas emissions; most of these emissions come from burning coal. Two significant mitigation opportunities exist for the power generation sector. The first is the development of carbon sequestration services for the long-term storage of CO_2 emissions from power plants in Pennsylvania, or even in other states. The second is the development of energy-efficiency and demand response services to encourage electricity customers to reduce peak power demands, and to invest in appliances and devices that use less electricity. The Commonwealth has already put in place initial policies to promote both of these opportunities.

10.4.2.1 The Need to Maintain Electric Reliability

Electricity is a vital commodity for modern business and life, and interruptions in electric service are very costly. The northeastern blackout of August 2003, interrupted 50 million electric customers and resulted in $6 billion in damages and lost productivity to the U.S. economy. Transmission and generation investments to promote reliability have been lagging in a number of regions of the U.S., including PJM. Climate change and high levels of electric reliability are social goals that may, at times, be at odds. Environmental regulations such as cap-and-trade systems or annual output limits can constrain existing generation plants during times of peak demand, potentially forcing a choice between rolling blackouts or violating environmental regulations. Environmental constraints played a role in California's energy crisis during the summer of 2000, since some emissions-constrained power plants were forced to shut down during times when demand was high and supply offers from competing generators were also high.

Maintaining reliable electric service in the PJM territory and in the Commonwealth, while simultaneously reducing the greenhouse gas impacts from electricity generation, will require a multi-pronged approach focusing on both supply-side and demand-side solutions. Many opportunities exist that can lower costs and promote new industries in Pennsylvania, without forcing sacrifices in quality of life.

10.4.2.2 Demand Reduction and Energy Efficiency Services

All of the climate models considered in this report predict some degree of future warming for Pennsylvania. Other things being equal, a warmer future for Pennsylvania is highly likely to increase peak electricity demand in Pennsylvania, due to rising cooling demand during the summertime. Meanwhile, wintertime electric heating demand is highly likely to decline. Such a decline in wintertime electricity demand also implies that peak electricity demand will grow faster than average electricity demand. Growth in peak demand is particularly problematic because meeting peak demand on the supply side involves the construction and dispatch of flexible but highly inefficient power plants. The need to construct peaking generation to meet as much as a 10 percent increase in peak generation (due to temperature alone) is a costly process that will increase electricity bills for all Pennsylvanians. Currently, many of these plants are fueled with refined petroleum, increasing the emissions impacts of peak electricity demand.

Reducing peak electricity demand through load-shifting (increasing some electricity use at night and decreasing some use during the day) would reduce the financial costs of climate change by reducing needed investments in peaking generation. Currently, PJM offers a number of different programs through which consumers can bid load reduction into the markets and receive payments for doing so (Apt, et al., 2007, Walawalkar, et al., 2008). Most of the participants in these programs are large customers, although a number of "curtailment service providers" exist throughout Pennsylvania that aggregate the demand-responsiveness of smaller customers, and interact with PJM on behalf of these customers.

Broader energy efficiency opportunities also exist, which would reduce electricity demand during all hours of the day. The Electric Power Research Institute (EPRI) has estimated that several gigawatts of energy efficiency investments across all sectors – the equivalent of several base-load power plants – could be achieved at less than the cost of building new capacity (Gellings, et al., 2006).

A number of states have initiated aggressive programs aimed at reducing peak demand and increasing energy efficiency. Through "utility revenue decoupling," where electric utilities are rewarded for demonstrable demand reductions, states such as California have achieved demand reductions at costs lower than wholesale market prices. Vermont has established an energy efficiency utility, Efficiency Vermont (www.efficiencyvermont.com), which is said to have reduced electricity demand by 7 percent at a cost of less than 4 cents per kWh (about one-third of the retail price in Vermont).

Pennsylvania has already taken some steps towards reducing peak demand and improving the efficiency of electric power use. Act 129 requires peak demand reductions of 4.5 percent and overall demand reductions of 3 percent by 2013 and requires the installation of advanced metering technologies, which are necessary for the use of time-differentiated pricing and PJM's demand response programs to reduce peak demand. In addition to these measures, Pennsylvania also should determine the best-practices of other states in achieving low-cost demand reductions, and focus on those policies and programs that can reduce electricity demand at a lower cost than the construction of new utility-scale peaking generation.

10.4.2.3 Co-generation and Self-generation

Additional emissions reduction opportunities in the electric power sector exist through increased use of co-generation and self-generation (or "distributed generation") technologies. Apt, et al. (2007) report that Pennsylvania companies already generate more than 1,000 MW of their own electricity, and have reported significant cost savings, particularly through the use of combined heat and power (CHP), where waste heat from the power generation process is used in industrial processes or to heat water. Co-generation systems have been known to achieve equivalent conversion efficiencies approaching 90 percent. (The most efficient new natural gas plants have conversion efficiencies of around 60 percent.) It is important to realize that since PJM is a regionally integrated electricity market, the use of cost-effective co-generation and self-generation can not only reduce emissions, but lowers costs for all users on the system since the construction of new generation, transmission and distribution facilities is avoided.

As discussed in Section 7, methane digesters represent one opportunity for Pennsylvania's agricultural sector to reduce greenhouse gas emissions while increasing the Commonwealth's supply of low-emissions energy. At current electricity and natural gas prices, these digesters would only be cost-effective in certain situations. Digesters also do not entirely eliminate the need for agricultural waste-management practices to maintain water quality, as discussed in Section 5.

Pennsylvania is considered a leader in "net metering" regulations, that allow the owners of self-generation systems to sell excess power back to the utility (Network for New Energy Choices, 2008). The Commonwealth's Alternative Energy Investment Act and Special House Bill 1 provide funding for distributed energy and energy-efficiency projects for industrial, commercial and residential customers. Many of the technologies targeted in this legislation have the potential to reduce electricity demand significantly, particularly the demand for electric heating and cooling. One example is the use of ground-source or geothermal heat pumps for residential or district heating and cooling, as shown in Figure 10.17 (Blumsack, et al., 2009).

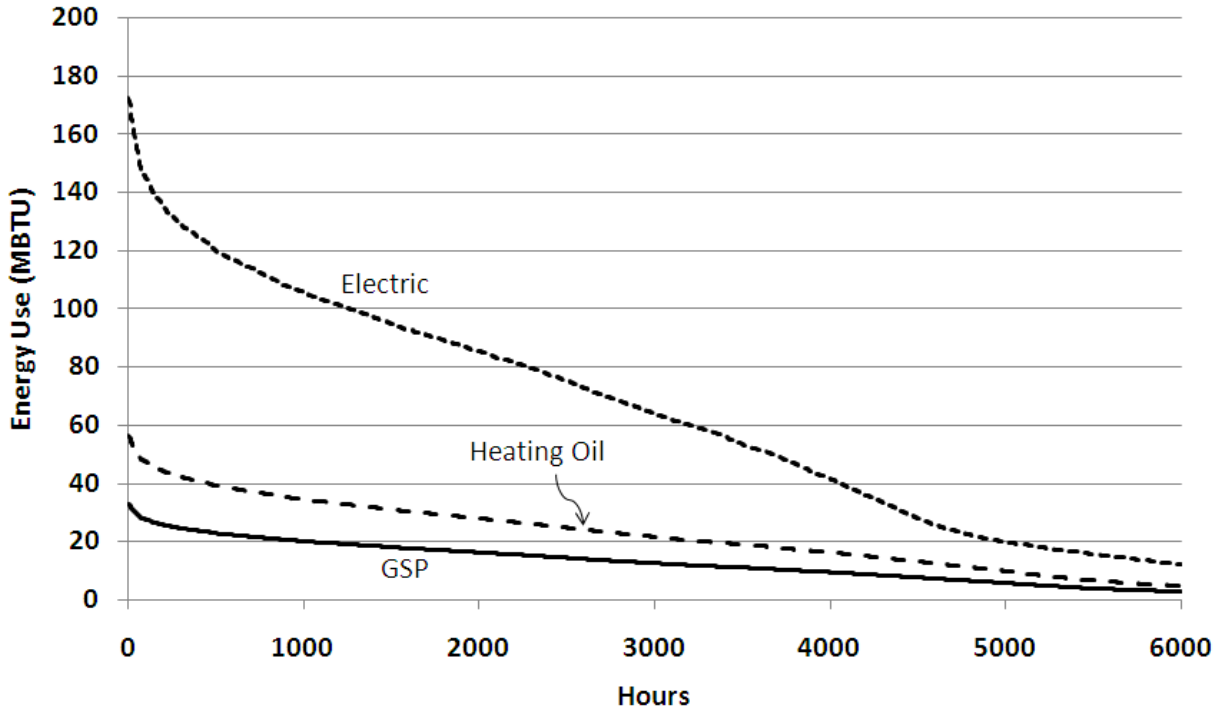


Figure 10.17. Cumulative energy use for heating and cooling in a Pennsylvania household using electric, fuel oil and ground-source heat pump (GSP) systems. Source: Blumsack, et al. (2009).

Other opportunities may be available to reduce emissions and lower costs through co-generation or self-generation "micro-grids," particularly in malls, campuses or office parks that demand both electricity and heat. The barrier to establishing a micro-grid is the exclusive right given to an electric utility to provide service in a geographic area; micro-grids are not explicitly defined under Pennsylvania law. By clarifying its laws to permit the development of micro-grids where cost-effective, the Commonwealth could further encourage the development of businesses that install and maintain distributed generation and co-generation equipment.

10.4.3 Synergies Between Low-Carbon Transportation and Electric Power

Plug-in hybrid vehicles (PHEVs) have the potential to reduce emissions from Pennsylvania's transportation sector, if the electric power sector can also be de-carbonized through the adoption of low-emissions generation technologies or carbon capture and sequestration. Development of an electrified transportation sector based on PHEVs may also create synergies between the development of alternative generation sources (particularly intermittent resources such as solar and wind power). The intermittent nature of these resources creates challenges for PJM and other system operators, since conventional system operation requires that other power plants be ramped up and backed down to accommodate fluctuations in wind power output (Apt, 2007). The inefficient operation of conventional power plants in this way may actually increase emissions of some pollutants, and large-scale development of wind generation in Pennsylvania or elsewhere in the PJM footprint may require the parallel development of backup generators, further increasing costs.

Many large-scale renewable resources are located far from demand centers, so an extensive transmission network would be required to deliver energy from these sources to end-use customers. The cost of transmission facilities has increased rapidly in recent years, driven primarily by increases in the cost of raw materials. At a national level, the transmission network required to deliver large amounts of Midwestern wind power to Eastern demand centers would likely require thousands of circuit-miles of new high-voltage transmission costing tens of billions of dollars (AEP, 2008). Additional challenges are posed by increasing siting and permitting difficulties for transmission construction. Many states that face serious transmission constraints, including Pennsylvania, also face barriers to getting transmission built (Vajjhalla and Fischbeck, 2007).

The potential for PHEVs is to act as distributed storage devices for wind and solar power, reducing some of the costs associated with resource intermittency. The vehicle batteries would charge during periods when power output was high, and would cease charging when wind power output died down. PHEVs could also be used to supply power to the grid during peak times, avoiding the need for new peaking plants and avoiding some emissions from existing peaking plants (Kempton and Tomic 2005). Advanced metering and similar "smart grid" communications and control technologies would need to be widely deployed before these synergies could be fully enjoyed. The Commonwealth should consider adopting a regulatory framework above and beyond that in Act 129 to promote "smart grid" pilot projects with the state's utilities.

Additional synergies may be enjoyed between the development of a PHEV-based transportation infrastructure and the development of Pennsylvania's biofuel potential. At a national level, biofuels such as ethanol cannot fully substitute for petroleum fuel (Griffin and Lave 2006). PHEVs, however, require significantly less liquid fuel than conventional vehicles. Using electricity as a fuel source for vehicles could allow more petroleum-based fuel to be displaced with ethanol or other biofuels.

10.5 Uncertainties and Information Needs

Policies and planning related to energy production and consumption often result in path-dependencies, where current choices lock society into infrastructures and systems for years or decades into the future. Several of the potential climate-related mitigation and adaptation opportunities for energy production and use in Pennsylvania are characterized by high levels of regulatory, financial or technological uncertainty. More information and analysis is required before policies are enacted that effectively commit the Commonwealth and its economy down any specific energy pathway. Investments in the energy sector are inherently long-lived (infrastructure-dependent, high fixed costs, etc), and policy will play a role in determining which investments happen and which do not. Serious analysis would be necessary for consideration of the high-level implications, including critical uncertainties.

Regulatory uncertainty surrounding state or federal climate policy is perhaps the largest barrier to mitigating and adapting to climate change in Pennsylvania's energy sector. Virtually all of the policy options, technologies and opportunities discussed in this section lose much of their economic appeal without a serious commitment to carbon regulation soon. Such a regulatory commitment should not stop at simply placing a price on CO_2 emissions, but will require specific steps to attaining physical carbon emissions reductions, particularly from the electric power sector.

10.5.1 Information Needs for Developing Geologic Carbon Sequestration

Considerable uncertainty exists surrounding the prospects for large-scale geologic carbon sequestration in Pennsylvania. Much of this uncertainty is regulatory, as discussed in the Carbon Management Advisory Group report (DCNR, 2008) and also in Apt, et al. (2008) regarding property rights to pore space, separating storage rights from mineral rights, and liability issues associated with any possible leakage of carbon dioxide from sequestration sites. A further source of regulatory uncertainty surrounds rights-of-way for CO_2 pipelines, and whether transport pipelines are properly regulated by the state or by the FERC.

Compounding the regulatory uncertainty surrounding a legal framework for carbon sequestration in Pennsylvania is financial uncertainty. Particularly since the technologies to capture, transport, and geologically sequester carbon are new and relatively untested on a commercial scale, the private business case for sequestration-related services and infrastructure is questionable. As discussed in Apt, et al. (2008), the state will almost certainly need to play a major role in any demonstration project to prove the technical viability and public acceptability of carbon sequestration. More analysis and information is required on whether the Commonwealth simply needs to play a risk-transfer role by absorbing much of the perceived risk associated with carbon transport and sequestration technology, to enable private participation, or whether the state would need to assume outright ownership of any demonstration project and associated infrastructure.

10.5.2 Information Needs for Managing Future Peak Electricity Demand

While it is clear that opportunities exist for reducing peak electricity demand through time-differentiated electricity pricing and encouraging the adoption of energy-efficiency technologies, practices and building materials, adoption pathways and economically beneficial policies are not always as clear. The peak demand reduction goals set out in Act 129 are a start, but the smart-grid infrastructure and policies required to meet these goals go beyond advanced metering technology and time-differentiated electricity pricing.

The economic case for small-scale distributed energy and energy-efficient appliances have improved with rising fuel prices (Apt, et al., 2007; King and Morgan, 2007), and will improve further if a credible commitment can be made to pricing carbon dioxide and reducing emissions at the state and federal level. Further information is needed on likely consumer adoption rates for these technologies, and how policy can increase those adoption rates, if necessary. Consumers have historically demanded much faster payback times for energy-efficiency investments than for other sorts of investments. Further information and analysis is needed on whether the current set of state-offered incentives (through Act 129 and Act 1) is sufficient to significantly increase adoption rates.

10.6 Conclusions

Energy production and consumption play a major role in Pennsylvania's economy, and also in maintaining a high standard of living for Pennsylvanians. Since all of the climate models used in this report predict some degree of warming for Pennsylvania, in a business-as-usual scenario (without changes in consumer behaviors or mitigation policies directed at energy consumption), climate change is virtually certain increase the role that energy plays in the Commonwealth's economy, as warmer summers lead businesses and individuals to increase the use of air conditioning for indoor climate control. The role of a reliable and affordable supply of electricity is likely to increase in importance for Pennsylvania, particularly under high-growth scenarios or scenarios where transportation becomes electrified to a large degree. Perhaps most importantly, the impact of increased air-conditioning demand coupled with declining heating demand peak electricity demand implies that peak demand in Pennsylvania is highly likely grow at a faster rate than average demand growth. Peak electricity demand is expensive to serve, and poses reliability challenges to utilities and transmission system operators.

Placing a price on CO_2, through a tax or cap-and-trade system, is highly unlikely to in and of itself decarbonize Pennsylvania's electric power sector. The choice of technologies and policies for meeting increased electricity demand and eventually replacing the existing fossil-fired generation fleet are likely to play a significant role in how greenhouse gas emissions can be controlled in Pennsylvania, and the extent of any mitigation opportunities. Pennsylvania's AEPS and demand-reduction targets under Act 129 represent a first step, but a number of opportunities for increased energy efficiency and peak demand reduction remain. The Commonwealth's policies should focus on those areas with the highest potential returns – electricity demand reduction and a significant increase in customer self-generation, co-generation and energy-efficient space conditioning.

Electrification of transportation, particularly urban and suburban transportation, holds significant promise for decreasing greenhouse gas emissions from the transportation sector (assuming that electricity generation can be appropriately decarbonized), serving as distributed storage devices for absorbing variability in wind- and solar-power output, and potentially for meeting localized peak electricity demands. Both technological and regulatory progress will be required for electrified transportation to contribute significantly to climate impact mitigation and electric reliability.

Pennsylvania faces significant opportunities in the area of long-term geologic carbon sequestration. The sequestration assessment and risk assessment required as a part of Act 129 should serve as the starting point for a legal, regulatory and economic assessment of sequestration within the Commonwealth. For certain promising sequestration sites already identified by the DCNR and others, the Commonwealth will need to assess and consider any conflicts between sequestering carbon in shale formations and storing or producing natural gas from nearby or adjacent formations. A "first-mover" set of property rights is not necessarily in the interest of the Commonwealth. A property-rights regulatory framework, supported by a social cost-benefit assessment of competing uses for deep shale formations in Pennsylvania, will likely need to be established to handle conflicts between storage rights and mineral rights.

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11.0 Human Health

Weather can influence human health either directly or indirectly. An example of a direct effect is temperature stress, where the body has to work harder to maintain a constant core temperature when the outside temperature is very hot or very cold. Another example is injuries and deaths associated with extreme weather events such as floods or ice storms. Indirect effects are those where weather has a direct effect on some other factor that in turn affects human health. An example is summer smog, where high temperatures cause an increase in ground level ozone formation, which in turn affects respiratory health. Because human health is sensitive to weather, climate change will affect human health, sometimes positively and sometimes negatively.

Several different pathways of human health impact have been identified. These include:

- Mortality from temperature stress (heat and cold);
- Respiratory and heart disease caused by changes in air quality ;
- Mortality and injuries associated with extreme weather events;
- Changes in the geographical distribution and prevalence of vector-borne diseases and;
- Changes in water and air-borne infectious disease.

For some of these pathways, the direction of the effect on human health (positive or negative) can be projected with fairly high confidence. For others, the direction is more difficult to project.

11.1 Temperature-related Mortality

11.1.1 The Relationship Between Temperature and Mortality

Much of the interest in temperature-related mortality has focused on extreme temperature events, particularly heat waves. However, research has shown that mortality can vary with temperature even within normal temperature ranges, and that cold weather also causes excess mortality. Most of the research on the relationship between temperature and mortality has been conducted by looking at daily temperature in a city and correlating that with daily mortality rates in that city. Time lags are included to capture delayed effects. These studies have consistently found a J-shaped relationship between average daily temperature and mortality. Figure 11.1 shows stylized versions of these J-curves for a typical mid-latitude U.S. city such as Philadelphia or Baltimore and a typical southern U.S. city such as Miami or Atlanta.

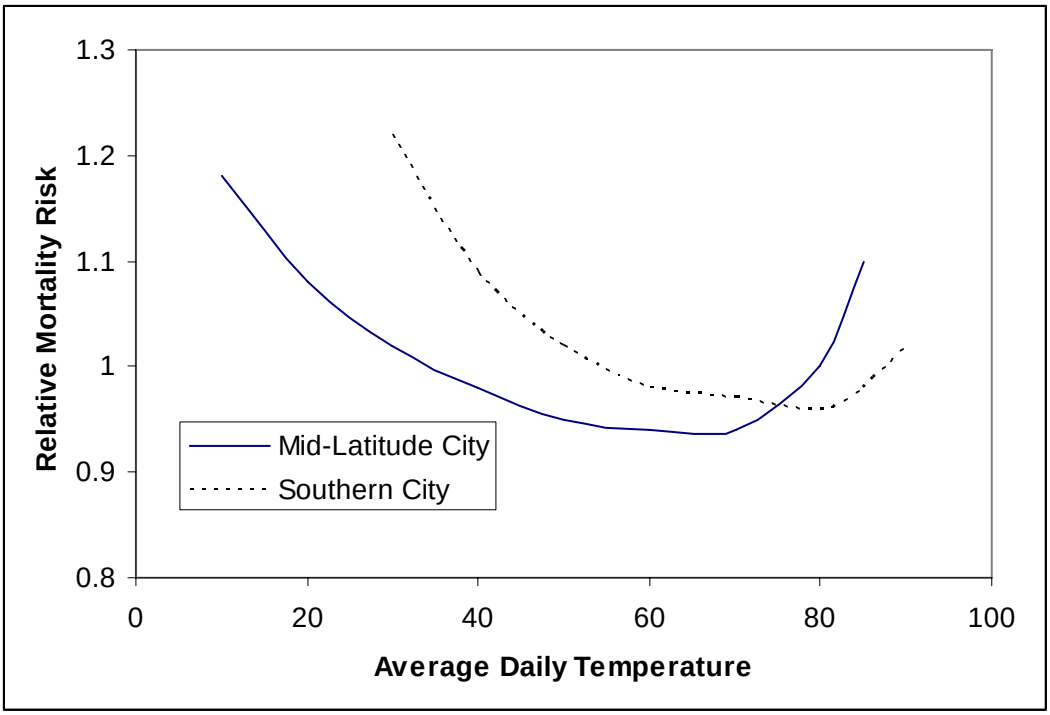

Figure 11.1. Typical "J" curves for a mid-latitude city such as Philadelphia or Pittsburgh and a southern city such as Miami or Atlanta

Figure 11.1 illustrates three features typical of J-curves found in research studies. First, there is an average daily temperature at which mortality rates are lowest[14]. For example, Curriero et al (2002) found that, in Philadelphia, this minimum mortality temperature was 71degrees F. Second, as temperature deviates in either direction from this minimum mortality temperature, the mortality rate increases, but the increase tends to be steeper for warmer temperatures than for cooler temperatures, particularly for mid-latitude and northern cities. Third, the minimum mortality temperature or temperature range varies from city to city. In cities with higher average annual temperatures, the bottom of the J-curve tends to be shifted to the right. For example, in the Curriero et al study, the minimum mortality temperature in Atlanta was 76 degrees F, while in Miami and Tampa it was 81 degrees F. This shift is thought to be due to adaptation of the population to local conditions.

There is some evidence that the tails of the J-curve get steeper as temperatures become more extreme, so that the impact of an increase in average daily temperature from, for example, 90 degrees F to 95 degrees F would be greater than the impact of an increase from 85 degrees F to 90 degrees F (Hajat et al 2006). However, this non-linearity is not always seen, and when found tends to be small.

[14] In some studies, there is a range of temperatures where the J-curve is relatively flat.

While heat and cold both cause excess mortality, winter temperatures in Pennsylvania deviate more from the minimum mortality temperature than do summer temperatures. The net effect is that winter mortality rates are higher than summer mortality rates. Figure 11.2 shows the monthly death rate for all Pennsylvania residents, calculated from 2006 data. The death rate averaged over cold months (December, January, February and March) was 14 percent higher than the average for warm months (June through September). This pattern is consistent with national mortality statistics.

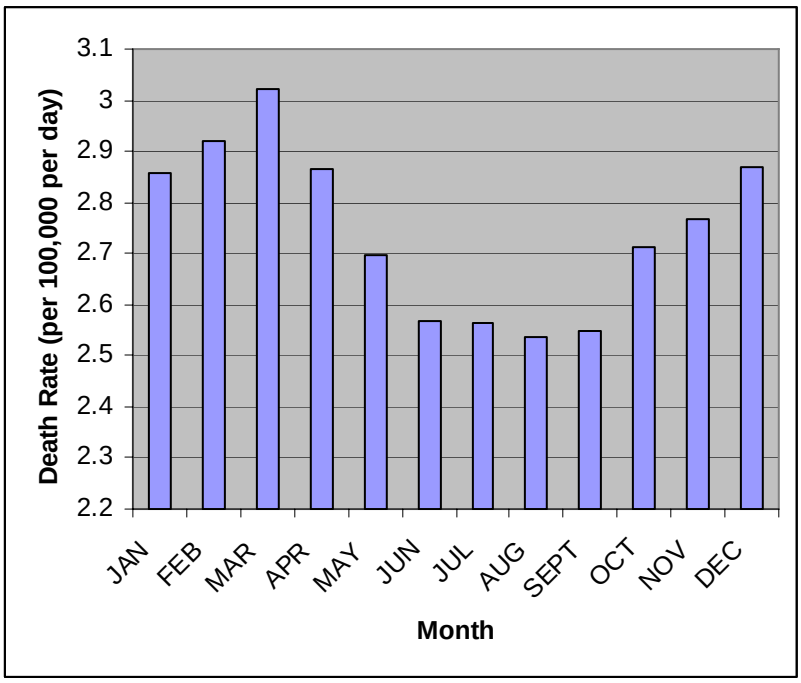

Figure 11.2. Pennsylvania Death Rate by month in 2006 (Source: PA Department of Health)

11.1.2 Mechanisms

Temperature can influence mortality either directly or indirectly. Direct effects are those that are associated with cold or heat stress. Under both cold and warm temperatures, the body must work harder to maintain a constant core body temperature. The heart must pump faster to deliver blood to the body surface to maintain warmth in cold conditions or to cool the core in warm conditions. This can lead to cardiovascular mortality, particularly among elderly.

Indirect effects are those where the mechanism involves some intermediate factor between temperature and mortality. An example would be mortality associated with respiratory infections, which are more prevalent during colder periods. Another example would be mortality associated with increased ozone concentrations due to higher summer temperatures.

Direct temperature-related mortality mechanisms tend to be more immediate than indirect mechanisms. By exploring whether there exist lags in the relationship between daily temperature and mortality, it is possible to learn something about the relative importance of direct versus indirect mechanisms. Studies have tended to find excess mortality associated with heat occurs mostly immediately, while the excess mortality associated with cold is spread out up to two weeks after the cold weather (Deschenes and Moretti 2007). This suggests that indirect mechanisms are more important for cold-related mortality, while direct mechanisms dominate heat-related mortality.

In developed countries, it has been observed that increases in mortality rates associated with heat events tend to be followed by a subsequent decrease in mortality. This is evidence that some portion of heat-related mortality represents near-term displacement, where a death that would have otherwise occurred without the temperature stress is hastened by the weather event. (Deschenes and Moretti 2007, Hajat et al 2005). However, in very extreme heat events, near-term displacement appears to be less important (Le Tertre et al. 2006; Medina-Ramon and Schwartz 2007). In contrast, increased mortality associated with cold events is not followed by a subsequent decrease in mortality, suggesting that near-term displacement does not play an important role in cold-related mortality (Deschenes and Moretti 2007).

11.1.3 Impact of Climate Change on Mortality

Projections of climate change indicate that average temperatures in Pennsylvania will be warmer year-round, with little difference in winter warming versus summer warming. Thus, excess mortality in winter due to cold will decrease while excess mortality in summer due to heat will increase. Whether the net effect will be an increase or a decrease in total annual mortality depends on two things. First, in Pennsylvania, the cool season (when the average temperature is less than the minimum mortality temperature) is longer than the warm season. This means that the mortality decrease from warming during the cool season lasts longer than the mortality increase from warming during the warm season. However, the marginal impact on mortality of warming is greater during the

warm season than during the cool season. Using the coefficients estimated by Curriero et al, and weather records for Philadelphia, the cool season is about three times as long as the warm season, but the slope of the left hand tail of the J-curve estimated for Philadelphia is about 70 percent as steep as the slope of the right hand tail. Combining the two effects, the decrease in mortality from warming during the cool season outweighs the increase in mortality from warming during the warm season in Philadelphia.

However, there are several factors complicating this simple analysis. While time-series studies of temperature and mortality are useful, longer term changes in climate could affect mortality in ways that are different from short term variations in temperature. For example, one mechanism that can lead to cold-related mortality is an increase in flu incidence associated with spending more time indoors. However, there is little evidence that residents of warmer climates suffer less flu than residents of colder climates. So the relationship between cold and mortality estimated from time-series studies would tend to overstate the impact that climate change would have on mortality.

At the same time, the differences in the location and shape of the J-curves estimated for mid-latitude versus southern cities shows the influence that adaptation can have on temperature-related mortality. A consistent finding is that minimum mortality temperature are higher in cities that have higher average temperatures, showing that populations can adapt to warmer climates, lessening the incidence of heat-related deaths. Indeed, in some warmer cities, a relationship between heat and mortality cannot be established. This suggests that vulnerability to heat related deaths can be modified through behavioral responses, changes in physiology, and changes in the built environment (particularly air conditioning).

There is also evidence that over time the population has become less susceptible to heat-related deaths. Davis et al (2003) found that the number of excess deaths associated with heat events has decreased over the last four decades. For Pittsburgh and Philadelphia, heat related excess mortality fell by about 75 percent over that time. Fouillet et al (2008) found a similar decrease in excess mortality from heat waves in France. A similar decrease in sensitivity to cold has been observed in Europe (Carson et al 2006)

These findings, showing both spatial and temporal changes in vulnerability, suggest that Pennsylvania residents will take adaptive actions to minimize heat impacts as our climate warms, weakening the relationship between temperature and mortality and lessening any impact that climate change would have on mortality.

Finally, it must be remembered that a large proportion of heat-related mortality represents near-term displacement of less than one week, while such displacement is less important for cold-related mortality. Near-term displacement would not influence mortality rates measured over longer periods, such as a year.

Taking all of these factors together, it is not possible to conclusively predict whether an increase in average winter and summer temperatures will lead to an increase or decrease in annual mortality rates in Pennsylvania. There certainly is no consensus among

researchers. Medina-Ramon and Schwartz (2007) argue that, for the U.S. as a whole, the increase in heat-related deaths will outweigh the decrease in cold-related deaths. In contrast, Donaldson et al (2001), project for the United Kingdom that the reduction in cold season deaths will outweigh the increase in warm season deaths. Similarly, Morten (1998) predicts that climate change would reduce total mortality in both Canada and the U.S.

11.2 Air Quality Impacts

In addition to heat and cold stress, climate can affect health indirectly through its impacts on other factors that affect health. Of particular importance are the impacts that temperature, wind and precipitation can have on various air quality measures (Bernard et al 2001).

11.2.1 Ground-level Ozone Formation

The most important mechanism for formation of ground-level ozone is chemical reactions when nitrogen oxides and/or volatile organic compounds in the air are exposed to sunlight. The rate of ozone formation increases with greater sunlight and with higher temperatures (Kinney 2008). The relationship between temperature and ozone concentration can be seen in Figure 11.3, which shows daily data from Pittsburgh for the 2008 warm season.

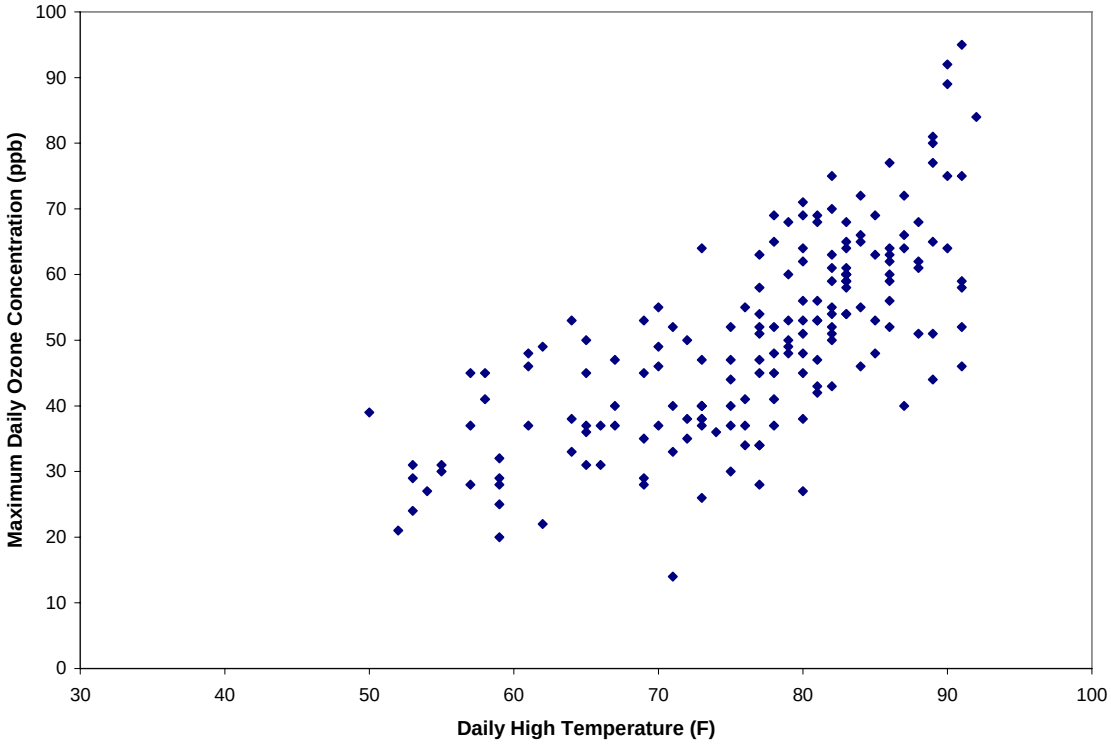

Figure 11.3. Ozone concentrations tend to be higher on warmer days. Data from Pittsburgh, May through October 2008. Data source: PA DEP.

Ozone is a respiratory irritant that damages the cells lining the lungs. Exposure to ozone causes respiratory symptoms such as coughing, shortness of breath, and discomfort in the chest when breathing. Epidemiological studies have associated exposure to higher ozone concentrations with increased hospital admissions for respiratory ailments, aggravation of asthma, and increased risk of respiratory infections. Ozone can negatively impact health at very low concentrations. The effects of ozone exposure are particularly acute for the elderly, children, persons with pre-existing respiratory disease such as asthma or COPD, and persons who work or exercise outdoors.

Fifteen Pennsylvania counties are classified by the EPA as nonattainment counties for the 8-hour ozone standard. These are concentrated in the southeast and southwest corners of the state, and include Philadelphia County and all counties contiguous with Philadelphia, plus Chester County, and Allegheny County (Pittsburgh) and all counties contiguous with Allegheny County, plus Indiana and Clearfield counties.

Climate change is expected to increase summer temperatures, which would increase the rate of ozone formation. Higher CO2 levels may also increase natural emissions of ozone precursor VOCs from vegetation (Lathiere et al 2005). Health impacts from ozone exposure are expected, therefore, to increase as a consequence of climate change. Hogrefe et al. (2004) projected the impact that climate change would have on ozone concentrations in the northeastern states, using the IPCC A2 scenario. To see the differential impact of climate change alone, their projections are made assuming the same rates of anthropogenic emissions as now. Their projections for ozone concentrations are shown in Figure 11.4. Summertime average daily maximum 8-hour ozone concentration is projected to increase in all of Pennsylvania. By 2020, the projected increase is in the range of 1.5 to 4.5 parts per billion (ppb) for most of Pennsylvania, with higher increases for Philadelphia and Pittsburgh. By 2080, ozone concentrations will increase by more than 7.5 ppb in all of southwestern Pennsylvania, and by more than 13.5 ppb in some parts of that area. Southeastern Pennsylvania will experience increases in the range of 4.5 to 10.5 ppb. The increases in ozone concentration in northern parts of the state will be much smaller (less than 4.5 ppb). So the largest increase in ozone concentrations from climate change will occur in the parts of the state that have the highest ozone concentrations now.

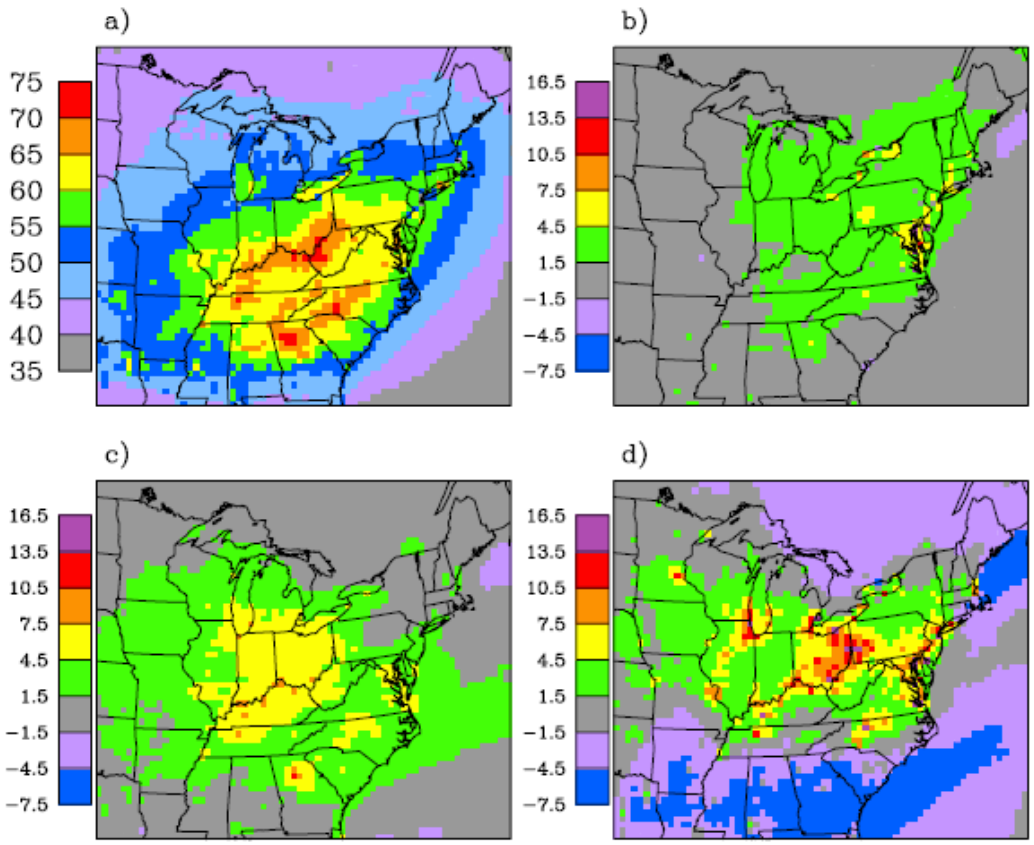

Figure 11.4. (a) Summertime average daily maximum 8-hour O3 concentrations for the 1990s and changes in summertime average daily maximum 8-hour O3 concentrations for the (b) 2020s, (c) 2050s, and (d) 2080s A2 scenario simulations relative to the 1990s, in parts per billion. (Source: Hogrefe et al 2004.)

Several studies have estimated dose-response relationships between air quality and health. These consistently show that exposure to ozone results in increased rates of hospital admission and mortality. For example, a study in London (Ponce de Leon et al 1996) found that an increase in 8-hour ozone concentration of 29 ppb resulted in an increase in hospital admissions of 4.83 percent. That is a much larger increase in ozone concentration than is projected to occur due to climate change. However, using linear interpolation, a 10 ppb increase in ambient ozone would be expected to result in a 1.4 percent increase in hospital admissions. A 10ppb increase is about what Hogrefe et al project as the increase in ozone concentrations due to climate change for Allegheny and Philadelphia Counties for the year 2080. Using current statistics for hospital admissions in these two counties, a 10 ppb increase in ozone would result in 426 additional hospital admission in Philadelphia County and 360 additional admissions in Allegheny County. Using an estimate of the average cost of a hospital admission that does not involve surgery of $12,631 (Taheri et al 2000), the increase in hospitalization due to increased ozone concentrations would result in over $4 million per year in increased medical costs just in these two counties. Changes in population and demographics would affect this estimate.

Ozone exposure can also lead to increased mortality. Bell et al (2004) found that a 10 ppb increase in ambient ozone leads to a 0.52 percent increase in the population mortality rate. If these two counties were to experience a 10 ppb increase in ozone concentration, given current population, we would expect 87 more deaths in Allegheny County and 103 more deaths in Philadelphia County each year as a consequence. It should be noted that to the extent higher ozone levels are a consequence of higher temperatures, part of this increased mortality would also be captured in the temperature-related mortality response discussed in Section I.

11.2.2 Particulates and Aerosols

Airborne particulates include dust particles, soot particles, and aerosols created by chemical reactions on SO2 and NO2 in the atmosphere. Particulate pollution causes many of the same respiratory symptoms as ozone exposure, but has also been shown to be associated with increased heart disease. Smaller particulates, those less than 2.5 microns in diameter, pose the largest health risk, because they are inhaled deeper into the lungs. The dominant source for these smaller particulates is combustion. EPA lists 17 Pennsylvania counties as being in nonattainment status for particulate (PM2.5) concentrations, and parts of two other counties. These are concentrated in southeastern Pennsylvania, around Harrisburg, Johnstown, and Pittsburgh.

The impact that climate change would have on airborne particulate concentrations is less well studied than for ozone. Several mechanisms have been proposed to motivate linkages. Increased wildfires would result in more particulate releases. Soot and aerosols from wildfires can travel long distances, so the increased wildfire activity would not have to be located in Pennsylvania to affect human health here. Changes in winds and rainfall patterns will affect dispersal of particulates, but in ways that are difficult to project.

Studies have shown that higher temperatures increase the rate at which combustion byproducts such as SO2 and NO2 convert to sulfate and nitrate particulates, but also increase the rate at which nitrate and organic particulates volatilize. Increased temperatures are therefore expected to lead to higher concentrations of sulfate particulates, but could result in either higher or lower concentration of organic and nitrate particulates (Aw and Kleeman 2003).

11.2.3 Pollen and Molds

Climate sensitive airborne allergens include pollen and molds. For sensitized individuals, exposure to airborne allergen can cause asthma, hay fever, and/or dermatitis. Because pollen and mold spores are released by living organisms, they are sensitive to climate.

For pollens, increased temperatures will result in earlier onset of pollen season, and longer pollen seasons. Earlier onset of pollen season has already been observed and associated with recent warming in Europe, and there is some limited evidence of lengthening of the pollen season and increased total pollen load (Kinney 2008; Alholm et

al 1998). Further, increased CO2 levels may affect pollen concentrations. Experiments have shown that plants grown under elevated CO2 concentrations release more pollen. For example, doubling the CO2 concentration from 300 to 600 ppm resulted in a four-fold increase in pollen production by ragweed (Ziska and Caufield 2000). Finally, climate changes will affect the distribution of pollen-producing plants. For example, Pennsylvania will see a shift in tree species. The impact that vegetation changes will have on pollen concentrations is difficult to forecast.

Less is known about the relationship between climate and mold spore concentrations. As with pollens, warmer temperatures will likely lengthen the season when outdoor molds are active. Changes in precipitation can also affect mold growth. Molds need moisture to grow, so increased precipitation could lead to more favorable conditions for mold growth (Kinney 2008). It has been speculated that increased variability in precipitation could lead to increased dispersion of mold spores carried on dust particles. This could lead to higher rates of pulmonary fungal infections, though the effect would be more prominent in arid areas where windblown soil is more of an issue (Bernard et al 2001).

11.3 Weather-related Accidents

11.3.1 Flooding

Floods are the largest cause of natural disaster related mortality, and inland flooding accounts for more than half of all flood deaths in the U.S. In Pennsylvania, weather-related flooding events that have caused large numbers of fatalities include tropical cyclones (for example Hurricane Agnes in 1982, which caused 50 deaths), rain-on-snow events (for example the floods of January 1996, which caused at least 18 deaths), and stalled weather systems that bring rain for a long period (for example the floods of June 2006, which caused at least 10 deaths).

Given current knowledge, it is impossible to project whether the likelihood of these types of extreme flood events will increase or decrease as a result of climate change. Because GCM models are not well suited to predicting individual short-duration rainfall events, little is known about what affect climate change will have on flood risk (IPCC WGII 2001). One study (Schreider et al. 1996) that attempted to project changes in flood frequently concluded that 50-year flood events in Australia would become 15-20 percent more frequent. The analysis presented in Section 3 indicated that wintertime precipitation will increase, and that storms will become more intense, as a result of climate change, so a similar expectation could exist for Pennsylvania.

However, it takes more than an intense rainstorm to cause severe flooding that result in large-scale loss of life. Because Pennsylvania will have less snow in the future, there is lower likelihood of a severe rain-on-snow event. There is no clear evidence whether climate change will affect the frequency of tropical storms, though there is some evidence that tropical storms may become more intense. Mid-latitude non-tropical cyclones are expected to be less frequent, but possibly more intense (Lambert and Fyfe 2006). Taken together, the net effect of these projections on the risk of severe flooding is uncertain.

Although individual flood events can cause many deaths, the average annual death toll from floods is small. Between 1997 and 2004, the average number of people killed in floods nationally was 81 per year, about the same number as from lightning strikes. If climate change does affect the risk of severe flooding, the statistical impact on human health is likely to be small.

11.3.2 Winter Storm Events

In Pennsylvania, 4.6 percent of motor vehicle accidents, and 2.9 percent of motor vehicle deaths occur when roads are slippery from winter weather (PennDOT 2007). In Pennsylvania, snow is expected less frequently, so the incidence of motor vehicle accidents and injuries associated with snow would be expected to decline. It is uncertain whether the number or intensity of freezing rain events will increase or decrease in Pennsylvania as a consequence of climate change.

However, the impact that winter weather has on accident rates, injury and deaths is not straightforward. Eisenberg and Warner (2005) found that motor vehicle accidents and accidents causing injury were higher on snowy days, but that fatal accidents were less frequent. They conjecture that this is due to a decrease in miles driven during winter weather along with a decrease in travel speeds. Studies in Canada (Brown and Baass 1997) and Scandinavia (Fridstrom et al 1995) had similar findings.

Winter storm events may be associated with accidents and health effects not related to motor vehicle accidents. Snowstorms are associated with higher rates of heart attack (Chowdhury et al 2003), through a combined effect of cold stress and exertion associated with snow removal. Ice storms in particular can results in injury-causing falls.

11.4 Infectious Disease

11.4.1 Vector-Borne Disease

The impact that climate change might have on the prevalence of vector-borne disease is of great concern in developing countries, but less of a concern in the United States because of advanced infrastructure, disease monitoring, and health care (Githeko et al 2000). Vector-borne diseases that are of concern in Pennsylvania include Lyme disease, encephalitis (including West Nile and St Louis Encephalitis), Ehrlichiosis, but probably not malaria. Climate can impact the prevalence of vector borne disease in several ways. First, it can affect the survival rate of the infectious agent (the bacteria or virus that causes the disease). Second, and perhaps most importantly, it can affect the population and distribution of the vector (the mosquito or tick that delivers the infectious agent). Third, it can affect the population of any intermediate hosts (other species of animals that host the infectious agent) or alternative prey of the vector (animals that support the populations of the tick or mosquito but that do not necessarily become infected themselves).

Lyme Disease
Lyme disease is caused by infection by a bacterial agent (*Borrelia burgdorferi*). The vector that transmits the agent to humans is the blacklegged (deer) tick. During the tick's larval life stage in its first year, they feed on small mammals and birds, which serve as intermediate (reservoir) hosts for the agent. A particularly important intermediate host is white-footed mice. During the tick's nymph and adult stages, in its second year, it will feed on and transmit the agent to humans and other large animals such as dogs and deer.

Lyme disease is prevalent in northeastern and mid-west United States. Table 11.1 shows the number of reported cases in 2007 and incidence rate (per 100,000 residents) for the states with the highest prevalence, based on CDC statistics. Within Pennsylvania, reported cases are most heavily concentrated in southeastern Pennsylvania,

State	Reported Cases 2007	Incidence 2007
Connecticut	3058	87.3
Delaware	715	82.7
New Hampshire	896	68.1
Massachusetts	2988	46.3
Maryland	2576	45.8
Maine	529	40.2
New Jersey	3134	36.1
Wisconsin	1814	32.4
Pennsylvania	3994	32.1
Minnesota	1238	23.8
Vermont	138	22.2
New York	4165	21.6
Rhode Island	177	16.7

Table 11.1. Lyme disease prevalence and incidence

Climate change could impact the distribution of the vector, the blacklegged tick. Brownstein et al (2005) project that the tick's suitable area will expand into Canada as a result of climate change, and will shrink in some areas of the southern United States. In their analysis, the distribution of the tick in Pennsylvania will not change much as a consequence of climate change. Although far northwestern Pennsylvania will become less suitable as habitat for the tick, the eastern two-thirds of the state will remain suitable.

In principle, if climate impacts populations of host species (most importantly white-footed mice and deer) it could affect Lyme disease risk. However, there is little empirical evidence that Lyme disease prevalence in ticks is directly related to either deer density or climate (precipitation and temperature). It has, however, been found to be highly correlated with density of mice and chipmunks (Ostfield et al. 2006). However, these are

fairly wide-ranging species, and climate change is not expected to have a large impact on their distribution or density.

Finally, climate change could affect human exposure to the agent. Increased temperatures will result in longer seasons when the nymph and adult stages of the tick are actively feeding. Warmer temperatures may also induce humans to spend more time outdoors in situations where they could be exposed to the ticks. Both affects would increase the potential for transmission and infection.

West Nile Disease

West Nile disease is a form of encephalitis. It is spread by mosquitos. The most important reservoir for the virus is birds. Some species of birds can die from the infection, but most infected birds survive. West Nile disease is endemic to Pennsylvania, though the number of cases reported is low relative to the Plains states and southwest United States. In 2007, there were 14 reported cases of West Nile disease in Pennsylvania. In most reported cases, the patient suffers from encephalitis or meningitis. The second most common outcome is a fever. Only in about 5 percent of reported cases is West Nile fatal. However, only severe cases tend to be reported. Of all cases (reported and nonreported) less than 1 percent of result in serious illness.

Because West Nile disease can survive in many different bird species, climate change is not likely to impact the availability of a reservoir host. West Nile is not very specific regarding the vector, either. Fourteen different species of mosquito have been shown to carry the disease (Peterson and Roehrig 2001). Spatial shifts in the distribution of any given mosquito species as a result of climate change is likely to have little impact on the disease prevalence. That the disease is endemic in almost all of continental U.S. is further evidence that its distribution is not climate sensitive.

A more likely mechanism through which climate change could impact disease incidence is through impacts on the mosquito density and exposure to mosquitos. But it is very difficult to predict mosquito population density based on climate. Mosquito populations are very sensitive to temperature and humidity. Mosquitos need wet areas to breed, and heavier or more frequent rainfall would increase the number of potential breeding sites. When breeding sites areas are available, the rate of development of mosquito larvae depends on temperature. With warmer temperatures, the mosquito life cycle can take place faster. This has two effects. First, mosquitos may be able to complete their life cycle in temporary pools of water before those pools dry up. Second, with shorter breeding cycles, populations can grow more quickly during wet periods. For these reasons, warmer temperatures and increased precipitation would be expected to increase mosquito densities.

Finally, as with Lyme disease, warmer temperatures would likely lengthen the mosquito breeding season, and thus lengthen the duration when West Nile infection can occur. Further, warmer temperatures would likely increase the amount of time that humans spend in outdoor activities, further increasing exposure to infection.

St. Louis Encephalitis
St Louis Encephalitis is closely related to West Nile virus, and is also transmitted by mosquitos with birds serving as reservoir hosts. Except for occasional outbreaks, there are fewer reported cases each year of St Louis Encephalitis than there are of West Nile disease. However, the vast majority of St Louis Encephalitis cases are mild and never reported. Between 1964 and 2006, there were 37 reported cases of St Louis Encephalitis in Pennsylvania. States with higher rates of reported cases include Texas, Mississippi, Florida, Ohio, Indiana and Illinois.

The same factors that determine the sensitivity of West Nile disease to climate change would apply for St. Louis Encephalitis. Climate change would not likely impact the distribution of the disease, but it could affect incidence rates through its impacts on mosquito density and frequency of outdoor activity.

Ehrilichiosis
Ehrlichiosis is a tick-borne bacterial disease. It is far less common than Lyme Disease. From 1986 to 1997, 1200 cases were reported to the CDC. In contrast, there were over 25,000 cases of Lyme disease reported in 2007 alone.

Two forms of Ehrlichiosis exist, HME and HGE, which differ in the type of infection that occurs, and the vectors that carry them. These different forms are carried by different vectors. The principle vector for HME is the Lone Star Tick. Its range includes Virginia, parts of Maryland, and New Jersey, but it is not common in Pennsylvania. The principle vector for HGE is the blacklegged tick, the same vector that carries Lyme disease. The distribution of HGE cases is therefore similar to the distribution of Lyme disease cases.

As with Lyme disease, the most important impact that climate change might have on Ehrlichiosis incidence is through warming, which would lengthen the season when ticks are active, and increase human activity in outdoor areas where ticks are present. One possible additional issue is that warming might expand the range of the Lone Star Tick, so that the HME form of the disease becomes established in Pennsylvania.

Malaria
Malaria is a parasitic disease spread by mosquitos. One hundred years ago, malaria was endemic in most of the continental United States east of the Rocky Mountains, except for the Appalachian chain and New England. After World War II, the National Malaria Eradication Program, through a combination of drainage, removal of breeding sites, and spraying, eliminated malaria from the U.S. By 1951, malaria was considered eradicated in the U.S. Currently, about 1000 cases of malaria are diagnosed in the U.S. each year, but are thought to be the result of infections contracted in other countries.

If Pennsylvania becomes warmer and wetter, it could become more conducive to supporting the mosquito species that can carry malaria. Still, malaria would have to be reintroduced to the United States. Given infrastructure and disease monitoring capabilities in the U.S., it is unlikely that malaria would become endemic in the United

States again. However, there may be some isolated incidents of infection originating with imported cases of the disease (Gubler et al. 2001).

11.4.2 Water-Borne Disease

Climate change has the potential to increase pathogen loads in surface waters. The most important mechanism is through increased precipitation. Increased rainfall and/or more intense rainfall events can transport pathogens, for example from farms with livestock, to streams and rivers. Increased precipitation also increases human sewage discharges to streams and rivers. In combined sewer systems that carry both stormwater and sewage, sewers are designed to overflow to surface waters during heavy rain events. But even in dedicated sewage only systems, infiltration can overload the system, resulting in overflows. While increased precipitation is the most likely mechanism through which water-borne contamination would increase, the survival of pathogens in the water can also be enhanced by higher temperatures.

There are three main routes by which water-borne disease can infect humans, through drinking water, through direct contact with surface water (for example when swimming), and through transmission on food.

Compared to developing countries, Pennsylvania has a very safe drinking water supply, because it can afford to invest in drinking water treatment and monitoring. There is still the potential for isolated disease outbreaks from poorly protected and/or improperly treated drinking water. In 1993, an outbreak of Cryptosporidium in the public water supply of Milwaukee, Wis., sickened 400,000 people and killed 100. Subsequent investigation showed that the infection source was human sewage. Heavy rains may have caused sewer overflows into Lake Michigan that were carried by currents to a water treatment plant intake. In 2000, 2,300 illnesses and seven deaths were caused by an outbreak of E. coli in the public water supply of Walkertown, Ontario. Investigation showed that the source was livestock located close to a water supply well. Heavy rains just prior to the event likely aided the transport of the pathogens through fractured bedrock. In both cases, the contamination would have been controlled if adequate treatment had been in place.

Rates of gastroenteritis show a strong seasonal pattern, where infection rates are higher in summer. This is particularly true for Campylobacter and Salmonella infections (Greer et al 2008). This is most likely due to increased exposure through direct contact with surface water. Warmer temperatures will likely result in increased water-based recreation (see Section 12). Both participation rates and season duration are likely to increase. Higher infection rates are therefore expected both because of increased pathogen loads in surface water from increased precipitation and temperature, and due to increased exposure from increased participation in water based recreation.

Irrigation of fruits and vegetables with contaminated water can cause disease outbreak. In 2006, a national outbreak of E coli traced to fresh spinach produced in central California sickened 200 and killed three people. In Pennsylvania, less than 1 percent of

farmland is irrigated, and the amount of irrigated farmland has not been increasing (USDA Census of Agriculture). As a public health concern in Pennsylvania, contamination of irrigated produce from outside Pennsylvania is more of a concern.

11.4.3 Air-Borne Disease

Infectious respiratory diseases such as influenza and pneumococcus have distinct seasonal infection patterns, with higher rates of infection during winter months (Greer et al 2008). This pattern is likely due to increased time spent indoors and to decreased indoor humidity levels that improves pathogen survival and transmission (Shaman and Kohn 2009). In Pennsylvania, winters are expected to be shorter, warmer, and wetter. This should result in fewer cases of pneumonia. This reduction in pneumonia is one of the factors that motivate the decrease in winter deaths discussed in section I.

For influenza, however, the impact that climate change might have is less well established. There is evidence from looking at El Nino events that influenza infection rates are sensitive to climate variation (Choi et al 2006; Viboud et al 2004). However, if influenza were sensitive to temperature and precipitation, one would expect to see differences in infection rates between colder and warmer climates. However, while warmer areas show less seasonality in flu incidence, total flu incidence is not necessarily different from that in colder areas (Viboud et al 2006). It may be that in temperate regions climate determines the timing of influenza, but not the total burden. It is therefore difficult to predict what impact climate change might have on influenza incidence.

11.5 Adaptation Opportunities

Some of the potential impacts of climate change on public health are speculative, while others are more certain. The health impacts with the highest level of confidence are a reduction in cold-related mortality, an increase in heat-related mortality, and an increase in respiratory disease resulting from increased ground level ozone formation. Health impacts with a moderate level of confidence are an increase in vector-borne disease from increased time spent outdoors and an increase in water-borne disease from increased participation in water-based outdoor recreation.

The increase in heat-related mortality will be moderated as Pennsylvanians individually adapt to higher summer temperatures, mostly through installation of air conditioning. As Pennsylvania's climate becomes more like that of more southern states, Pennsylvania residents will adapt in ways similar to how residents in those states have already adapted. In 1997, 93 percent of homes in the southern region of the U.S. had air conditioning, while only 63 percent did in the northeastern region (source: U.S. Energy Information Administration Residential Energy Consumption Surveys). This will occur both as a result of retrofitting of existing properties and higher penetration in new homes. In 2007, more than 99 percent of new homes in the southern region had air conditioning, while only 75 percent did in the northeastern region (source: U.S. Census Characteristics of New Housing).

While most Pennsylvania residents will adapt to rising temperatures with installation and greater use of air conditioning, residents with limited resources will be unable to afford to install or operate air conditioning. Policies to minimize heat-related mortality should be targeted to these vulnerable populations. These policies could include programs to subsidize installation of air conditioning. Philadelphia instituted Hot Weather-Health Watch/Warning System in 1995 that has become a model for similar systems worldwide. It includes prediction of heat waves, a system to alert the public through the media, and interventions including home visits to vulnerable residents, increased emergency medical staffing, and providing access to air conditioned spaces. It has been estimated that Philadelphia's system prevented 117 deaths in the first four years of its operation (Ebi et al 2004).

Individual households have less opportunity to self-protect from increased smog in the summertime, though air conditioning does provide some protection by allowing people to stay indoors during periods with poor air quality. The most important adaptation that could be made to reduce summer smog formation is a reduction in the emissions VOC's and nitrogen oxides.

For both heat-related mortality and summertime smog formation, another important means of adaptation would be to take actions to decrease urban heat island effects. In summer, dark pavement and building surfaces absorb sunlight and radiate heat, increasing temperatures in urban areas relative to areas with less impermeable surface and more vegetation. Exhaust heat from businesses, homes, and cars can add to the effect. Adaptations include use of paving materials that absorb less heat, reflective roof coatings, and increasing tree and vegetative cover.

As discussed above, it is not clear whether vector-borne diseases such as Lyme Disease and West Nile Disease will become more prevalent in Pennsylvania as a result of climate change. Continued disease monitoring is important. However, it is likely that human exposure to the vectors will increase, as the outdoor recreation season lengthens. Public education about actions that can be taken to minimize the risk of infection will be an important tool to limit the potential increase in disease associated with increased exposure.

Similarly, while it is not clear that climate change would increase pathogen loads in surface water, it is likely that higher temperatures will lead residents to engage in water-based recreation (swimming, boating, etc.) more frequently, and for a longer season. Actions should be taken to reduce pathogen loads to streams and lakes from agricultural and human sources, to monitor bathing water quality at popular bathing sites, and to educate users on ways to minimize the risk of disease from contact with surface water.

11.6 Mitigation Barriers and Opportunities

Most actions taken by households to enhance their health or protect it from weather-related risks have little impact on GHG emissions. One exception is the purchase and use of air conditioning as a way of adapting to higher summer temperatures. The use of air

conditioning has been important in reducing heat-related mortality in southern cities, and is expected to increase in Pennsylvania. Unfortunately, increased use of air conditioning will increase summer energy demand, and increase peak energy demand.

11.7 Information Needs

Much of the uncertainty over the potential impacts of climate change on human health in Pennsylvania is due to uncertainties over the basic relationships between climate and health. For example, it is fairly well established that heat events in summer cause excess mortality, and that cold in winter does as well. It is less clear, however, whether a year-round warming would result in a net increase or decrease in temperature-related mortality. As another example, while it is clear that higher concentrations of air-borne particulates cause increased respiratory and heart disease, the impact that climate change will have on particulate concentrations is uncertain. As a third example, there are laboratory experiments that show that higher temperature and CO2 concentrations can increase pollen production by plants, but little is known about whether these would translate to higher pollen loads outside the laboratory. More research is needed to resolve these uncertainties over potential climate change impacts.

The research described in the previous paragraph is not specific to Pennsylvania. The most pressing information needs specific to Pennsylvania are those where information is needed to effectively adapt to climate change. These include research on:

- Factors that promote urban heat island effects in Pennsylvania cities, and the effectiveness of actions taken to reduce UHI effects;
- Factors that promote ozone formation in Pennsylvania cities, and the effectiveness of actions taken to reduce ozone precursors;
- Identification of drinking water systems that are vulnerable to contamination by water-borne disease, due to improper or incomplete treatment and;
- How human behavior will change as a consequence of climate change, how those behavior changes will affect human health, and the potential for public education as a means of encouraging individual adaptation to climate change in ways that promote health.

In addition, continuous monitoring of health indicators would allow the state to adapt if climate change is found to affect disease prevalence. Examples of such health indicators include:

- Criteria air pollutants;
- Pollen loads;
- The distribution and prevalence of vector-borne diseases;
- Concentrations of water-borne pathogens in surface waters, especially at recreation sites and;
- Incidence of respiratory disease such as influenza and pneumonia.

Finally, while Pennsylvania has been a worldwide leader in developing methods to reduce mortality from hot weather, little is known about the adaptive measures that could be taken to reduce mortality from cold weather. While cold weather is expected to decrease with climate change, there is still a need to conduct research on the mechanisms of cold-related mortality and on possible interventions to reduce cold-related mortality.

11.8 Conclusions

Year-round increases in temperature will have several impacts on human health. Increased summer heat will cause more heat-related deaths. The direction of this impact is established with high confidence. However, as residents install and increase use of air conditioning, the population will become less vulnerable to extreme heat. This adaptation has already occurred in southern U.S. cities, and is expected to occur in Pennsylvania as well. A negative side effect of this adaptation is that increase air conditioning installation and use will increase energy demand, particularly during peak demand periods. While most Pennsylvania residents will adapt to rising temperatures with installation and greater use of air conditioning, residents with limited resources will be unable to afford to install or operate air conditioning. Policies to minimize heat-related mortality should be targeted to these vulnerable populations. These policies could include programs to subsidize installation of air conditioning. Warning and outreach programs such as Philadelphia's Hot Weather-Health Watch/Warning System have already proven themselves to reduce heat-related mortality.

Increased winter temperatures will mean fewer cold-related deaths. The direction of this impact is also established with high confidence. It is difficult to project which effect will dominate, but there is some evidence that the reduction in cold-related deaths will be larger than the increase in heat-related deaths.

Increased summer temperatures will result in increased formation of ground-level ozone. The direction of this impact is established with high confidence. Increased ozone concentrations have been shown to be related to higher incidence of respiratory disease and death. Individual households have few opportunities to self-protect from increased smog in the summertime, though air conditioning does provide some protection by allowing people to stay indoors during periods with poor air quality. The most important adaptation that could be made to reduce summer smog formation is a reduction in the emissions of VOCs and nitrogen oxides. A second adaptation that would reduce both heat-related mortality and summertime smog formation would be to take actions to decrease urban heat island effects. Adaptations include use of paving materials that absorb less heat, reflective roof coatings, and increasing tree and vegetative cover.

Increased summer temperatures may also result in higher concentrations of particulates, though the direction of this impact is established with low confidence. Higher particulate concentrations have been shown to be related to higher incidence of respiratory and heart disease. Similarly, higher summer temperatures and higher CO2 concentrations may result in higher concentrations of airborne allergens such as mold spores and pollen. The direction of this impact is also established with only low confidence.

Deaths and injuries from severe weather events such as floods and winter storms are not expected to change significantly as a consequence of climate change. While winter precipitation is expected to increase, because snow depth and coverage will decrease, there will be fewer rain-on-snow flood events. There may be an increase in summer floods due to increased variability in precipitation. As for winter storms, there will be fewer winter snowstorms and more winter rainstorms. The frequency of ice storms may decrease, but the direction of that impact is established with low confidence. Even if Pennsylvania were to experience more ice storms that would not necessarily imply higher traffic casualties. Death rates during ice storms are actually lower than during dry weather, due to adjustments made by drivers.

It is not clear whether vector-borne diseases such as Lyme Disease and West Nile Disease will become more prevalent in Pennsylvania as a result of climate change. Continued disease monitoring is important. However, warmer temperatures would lengthen the season during which the vectors that carry these diseases are active, increasing potential exposure. Further, warmer temperatures will likely result in people spending more time outdoors for a longer portion of the year, also increasing exposure. Public education about actions that can be taken to minimize the risk of infection will be an important tool to limit the potential increase in disease associated with increased exposure.

Increased precipitation will likely increase runoff that caries infectious pathogens, so that the risk of water-borne disease will increase. The direction of this impact is established with medium confidence. For most Pennsylvania residents, drinking water is well protected by treatment systems. A properly designed and well maintained public water system should be able to handle increased pathogen loads in source water without endangering public health. The more likely pathway for exposure is direct contact with surface water. With increased temperatures, water-based recreation is expected to increase, so that exposure to water-based disease will increase. Actions should be taken to reduce pathogen loads to streams and lakes from agricultural and human sources, to monitor bathing water quality at popular bathing sites, and to educate users on ways to minimize the risk of disease from contact with surface water.

It is difficult to predict what impact climate change might have on incidence of air-borne infectious disease. While air-borne diseases like influenza show a clear seasonal pattern that does not necessarily mean that changes in climate will change the overall, yearlong disease burden.

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12.0 Tourism and Outdoor Recreation

Pennsylvania is blessed with land and water resources that provide diverse outdoor recreation opportunities. Because of the nature of outdoor recreation, weather plays an important role in determining what type of outdoor recreation residents and tourists will engage in, and how often. Climate change can affect outdoor recreation participation in two ways. First, it can affect the recreation resource. For example, the distribution of wild trout is expected to shrink in Pennsylvania, affecting the recreational fishing resource. Second, climate change can affect the recreation experience directly, making some activities more or less enjoyable. For example, water-based recreation may become more attractive if summer temperatures are higher.

12.1 Outdoor Recreation Participation in Pennsylvania

Pennsylvanians participate in a wide range of outdoor activities. Table 12.1 includes estimates of the percent of Pennsylvanians aged 16 and older who participate in a variety of different activities, based on the National Survey of Recreation and the Environment (NSRE).

Activity	PA	US	Activity	PA	US
Fish and Wildlife Based Recreation			Land-based recreation		
Wildlife Viewing	48.0	44.1	Viewing natural scenery	62.3	59.5
Bird Viewing	36.0	31.8	Hiking	29.6	32.7
Freshwater Fishing	25.0	29.1	Camping - Developed	23.7	26.4
Warm-water Fishing	18.9	22.4	Mountain Biking	21.0	21.2
Coldwater Fishing	16.5	13.3	Off-Road Driving	17.8	17.4
Hunting	13.3	11.1	Camping - Primitive	12.7	15.9
Big Game Hunting	12.5	8.4	Backpacking	8.5	10.4
Small Game Hunting	8.5	7.1	Horseback Riding	6.9	9.6
Waterfowl Hunting	1.6	2.3			
Water-based Recreation			Non-nature-based Outdoor Sports		
Swimming	40.9	41.3	Swimming in an Outdoor Pool	45.9	n.a.
Visit Beach	39.6	40.9	Bicycling	35.5	39.4
Motorboating	18.1	24.3	Running or jogging	25.3	n.a.
Water Skiing	4.4	8.0	Golf	14.8	n.a.
Canoeing	9.1	9.6	Basketball	11.4	n.a.
Jet Skiing	6.5	9.5	Volleyball	11.3	n.a.
Sailing	4.4	5.2	Softball	10.7	n.a.
Rowing	3.9	4.3	Tennis Outdoors	8.9	n.a.
Kayaking	2.3	3.7	Baseball	7.7	n.a.
			Soccer	3.0	n.a.
Winter Recreation					
Sledding	22.5	n.a.			
Ice Skating Outdoors	8.4	n.a.			
Downhill Skiing	7.8	8.5			
Snowmobiling	5.8	5.5			

Snowboarding	5.0	4.9
Cross-Country Skiing	2.9	3.8

Table 12.1. Participation rate (percent) for selected outdoor recreation activities for Pennsylvania (source: PADCNR 2006, Appendix 2b) and the U.S. (source: USFS 2003)

Pennsylvanians have higher participation rates than the U.S. average in most fish and wildlife based recreation activities. Notable exceptions are warm-water fishing and waterfowl hunting. According to the NSRE, Pennsylvanians engage in most non-consumptive water and land-based recreation at lower rates than the U.S. average.

12.2 Snow-based Recreation

Climate models consistently project that Pennsylvania will have less total snowfall, shorter snow season, and less land area with snow cover as a consequence of climate change. While it is feasible to make snow when temperatures are low enough, this is practical only for downhill skiing. Cross-country skiing, snowmobiling, and sledding are dependent on natural snow. As a result of climate change, these activities will be feasible in fewer places in Pennsylvania, and for shorter seasons.

Downhill skiing in Pennsylvania is already dependent on man-made snow. Every downhill ski resort in Pennsylvania makes snow. As a result of climate change, ski resorts in Pennsylvania will receive less natural snow. This means that the resorts will need to make more man-made snow to maintain skiing quality. At the same time, climate change will mean that winter temperatures will be higher, so that there are fewer hours during the winter when snowmaking can take place. Snowmaking equipment operates most efficiently when it is colder and dryer. With traditional snowmaking equipment, it is possible to make snow when the wet-bulb temperature is below 28 degrees F. Snowmaking can be done at temperatures above 28 degrees F if the humidity is lower. New airless fan gun equipment is more energy efficient, makes snow more quickly, and can make snow at slightly higher temperatures, but the equipment is more expensive to purchase and install. Finally, ski seasons will be shorter. Of critical important to the economics of ski resorts is whether they are open for the Christmas-New Years holidays. Warmer December temperatures make it more likely that resorts will not be able to fully open before Christmas.

Scott et al (2008) analyzed the impact that climate change (using the A1Fi and B1 scenarios) would have on ski area operation throughout the Northeast. They modeled natural snowfall and snowmaking. They found under both emissions scenarios that during the 2010-2029 period, ski season length would shorten by 15 percent in both Eastern and Western Pennsylvania. By 2080-2099, ski season length would shorten by 29-32 percent under the B1 scenario, and by 46-50 percent under the A1Fi scenario. Further, they found that already by the 2010-2029 period, resorts in both Eastern and Western Pennsylvania would have a less than 75 percent probability of being open for the entire Christmas-New Years holiday. Under these conditions, resorts close to major metropolitan areas may be able to continue to operate by investing in snowmaking equipment to allow them to make

a deep base of snow quickly when conditions allow. Smaller resorts that serve smaller markets may not survive financially under those circumstances.

Because snowmaking is impractical, sledding, cross-country skiing and snowmobiling are more sensitive to climate change than is downhill skiing. Scott et al (2008), using the same model for natural snowfall as was used in the downhill skiing analysis, projected the impact that climate change would have on season length for snowmobiling. They defined the snowmobile season to be the number of days when natural snow depth was at least 15 cm (about 6 inches). They found that snowmobile seasons in Pennsylvania are already fairly short, relative to other Northeast states, and that they would become even shorter as a consequence of climate change. Table 12.2 summarizes their projections.

	Baseline	Low Emissions (B1)		High Emissions (A1Fi)	
Region	1961-90	2010-29	2070-99	2010-29	2070-99
Eastern Pa.	31	11	8	12	3
North Central Pa.	18	9	7	6	2
South Central Pa.	4	0	0	1	0

Table 12.2. Snowmobile season length (days).

Sledding is by far the winter recreation activity that is most frequently engaged in Pennsylvania. No analysis has been conducted on the impact of climate on sledding, or on cross country skiing. The snow needs for cross country skiing are similar to those for snowmobiling, though it can be done with less snow on smooth terrain such as golf courses and grassy areas in parks. The impact of climate change on cross country skiing should therefore be similar to that shown in Table 12.2. Sledding can be done on less snow cover. That means that season lengths (number of days per year when sledding is possible) would be longer than those shown in Table 12.2, but the impact of climate change on the sledding season could be similar in percentage terms.

12.3 Fishing

12.3.1 Recreational Fishing in Pennsylvania

According to the National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (NSFHWAR), 830,000 Pennsylvania residents aged 16 or older fished recreationally within the state in 2006, a participation rate of 8.4 percent. Pennsylvania residents enjoyed 17.1 million fishing days within the state, and spent $1.14 billion on equipment and trip related expenses. An additional 160,000 Pennsylvania residents fished recreationally, but only outside of Pennsylvania. Pennsylvania residents fished 3.5 million days outside of the state. Of these, about half were spent salt water fishing.

According to the same survey, 164,000 non-residents fished within the state. They enjoyed 839,000 fishing days in Pennsylvania, and spent $152 million in equipment and trip related expenses in the state. Non-residents comprised 17 percent of total anglers in Pennsylvania, but only about 12 percent of total angling expenditures. This is because, on

average, nonresidents fish fewer days than residents, and spend less money in the state on equipment.

Fishing participation has been declining. License sales have fallen by 25 percent since their peak in 1990. This decline matches a national trend.

Expenditures by residents and nonresidents in Pennsylvania stimulate additional economic activity. Sports angling has been estimated to have a total impact on economic activity in Pennsylvania of $4.75 billion, and to support 43,000 jobs in the state (Upneja et al 2001).

12.3.2 Climate Change Impacts on Cold-water and Warm-water Fishing

Climate change is expected to change the nature of the fishing resource. As temperatures warm, some habitat that is now suitable for cold-water species such as trout will become unsuitable. Where the physical habitat is suitable, warm-water species will inhabit some of these streams and lakes. However, some streams and lakes that currently support cold-water angling may not be suitable to support warm-water angling, meaning that the total fishing resource (warm-water plus cold-water) in the state could decline as a consequence of climate change.

Cold-water fishing is popular among anglers. About 2/3 of Pennsylvania anglers purchase a trout stamp when they purchase their fishing license. Similarly, the NSFHWAR estimates that 67 percent of anglers who fish in Pennsylvania target trout on at least some fishing trips. However, only 42 percent of fishing days in Pennsylvania are targeted toward trout. While most anglers fish for trout at least occasionally, most fishing activity in Pennsylvania is for warm-water species. This is true both for residents and nonresidents fishing in Pennsylvania.

Climate change would be expected to decrease the number of streams that support breeding populations of trout. Both changes in temperatures and changes in precipitation affect trout habitat suitability. Published projections of impacts in Pennsylvania are not available. However, a simulation study for the Appalachian region south of Pennsylvania found that a temperature increase of about 2 degrees C coupled with an increase in variability of precipitation resulted in a 24 percent decrease in brook trout habitat and a 16 percent decrease in rainbow trout habitat (Clark et al 2001).

While warmer temperatures would expand habitat suitable for warm water fish species, increased temperatures and changes in hydrology may have a negative effect on these species as well. High summer temperatures and low flows can result in low dissolved oxygen levels, stressing fish and making them more susceptible to disease.

12.3.3 Impacts on Ice Fishing

Data on participation in ice fishing in Pennsylvania is scarce. The NSRE estimated that 1.8 percent of Pennsylvanians engage in ice fishing, but that estimate is based on a very

small sample of residents. That estimate would imply that about 6 percent of Pennsylvania anglers participate in ice fishing.

The opportunity for ice fishing would be severely impacted by climate change. A simulation of ice formation (Fang and Stefan 1998) found that for small, medium-depth lakes, ice-in (the date when the lake freezes over) occurs on average in mid December for northern parts of the state and around New Years Day for central Pennsylvania. Under a scenario where atmospheric CO2 concentrations were doubled, ice-in occurs one to two weeks later. Ice-out dates (when the ice breaks up) are even more affected. For Pennsylvania, ice-out on small lakes would occur four to seven weeks earlier with a doubling of CO2 concentrations. Because ice fishing requires a sustained period of cold weather in order to form ice thick enough to support the activity, climate change associated with a doubling of CO2 concentrations would, in many years, completely eliminate the opportunity to ice fish on lakes that currently support the activity.

12.3.4 Impacts on Total Fishing Participation and Frequency

The best way to project the impact that climate change would have on aggregate fishing participation in Pennsylvania is by looking at participation rates in areas of the country that currently have a climate similar to Pennsylvania's future climate. This can be done informally by comparing Pennsylvania to other individual states, or it can be done in a statistical model that controls for other factors that vary among states.

An informal analysis shows that fishing participation tends to be higher in states with warmer climates. Table 12.3 shows the proportion of residents 16 years of age or older who participate in freshwater fishing (not including fishing in the Great Lakes) for four states, as well as the average number of days spent freshwater fishing per angler. There is a clear trend that the participation rate is higher in warmer states. There is no clear relationship between the days per participant and average temperature in the state. Days spent freshwater fishing per participant may be lower in Virginia, North Carolina, and Georgia because of competition with saltwater fishing.

State	Participation Rate	Days per participant	Days per resident
Pennsylvania	8.3 percent	20.5	1.7
Virginia	8.5 percent	12.7	1.1
North Carolina	11.4 percent	17.9	2.0
Georgia	13.1 percent	17.0	2.2

Table 12.3. Freshwater fishing participation rates and days spent fishing. Data source: National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (NSFHWAR).

Statistical analysis of national data confirms that fishing participation tends to be higher in states with higher average temperature. Mendelsohn and Markowski (1999) estimated a statistical model that explained variation among states in participation rates for several outdoor recreation activities. They found that the number of days spent fishing in a state

was consistently positively related to temperatures. This held for both freshwater and saltwater fishing.

To summarize, the expected impact of climate change on freshwater fishing in Pennsylvania is a decrease in fishing for coldwater species, an increase in fishing for warm-water species, a decrease in the opportunity for ice fishing, but an increase in overall fishing activity.

12.4 Hunting

According the NSFHWAR, 933,000 Pennsylvania residents hunted in Pennsylvania in 2006, a participation rate of 9.4 percent. Pennsylvania residents hunted 16.2 million days in the state, and spent $1.4 billion on hunting related expenditures. An additional 111,000 nonresidents hunted for 706,000 days in the state, and spent $162 million on hunting related expenditures.

Although climate change will affect the distribution of many wildlife species, the main game species in Pennsylvania (for example deer, bear, turkey, pheasant, ruffed grouse, small game) are broadly distributed. Their presence in Pennsylvania should not be affected by projected climate change. Some species may be affected by changes in habitat availability, however. For example, waterfowl are sensitive to wetland availability, which may be affected by climate change. As the species composition of Pennsylvania forests change in response to climate change, the abundance of some game species could change. For some species such as whitetail deer, mild winters with little snow could result in better winter survival and higher breeding success, leading to higher population densities.

While the animal resource may not change dramatically as a result of climate change, hunter behavior may be affected. Pennsylvania has a very high hunter participation rate, compared to nearby states. Table 12.4 shows the hunting participation rate for adults aged 16 and over for several states. While it is clear that hunting participation in Pennsylvania is higher than in nearby warmer states, there is not a consistent relationship between participation and climate across all states. Hunting participation in New York State is lower than any of the four states listed in Table 12.4.

State	Participation Rate	Days per participant	Days per resident
Pennsylvania	9.4 percent	17.3	1.6
Virginia	5.9 percent	17.8	1.1
North Carolina	4.0 percent	16.8	0.7
Georgia	4.8 percent	19.7	0.9

Table 12.4. Hunting participation rates and days spent hunting. Data source: NSFHWAR.

Statistical analysis of national data allows for control of confounding variables, and can include information from more states. Mendelsohn and Markowski (1999) estimated a statistical model explaining variation among states in the number of days spent hunting,

but found ambiguous results. In one model they estimated, an increase in temperature and precipitation increased hunting participation. In a second model, the same climate change decreased hunting participation. Their analysis suggests that hunting participation may be sensitive to climate change, but additional research is needed before conclusive statements about the direction of the impact can be made.

12.5 Swimming and Boating

Warmer temperatures are expected to increase participation in water-based recreation activities, both due to higher temperatures, which make water-based activities attractive, and due to longer recreation seasons. Mendelsohn and Markowski (1999) found that recreational boating activity was positively associated with higher summer temperatures. It was also positively associated with precipitation levels, but that effect likely captured differences in resource availability, rather than differences in behavior. Similarly, Loomis and Crespi (1999), in a study of reservoirs in the Western U.S., found that reservoir visitation was positively associated with average temperature. Ward et al (1995) in a study of reservoirs in several regions across the country also found that reservoir visitation was higher for reservoirs located in warmer areas. They found that a 10 percent increase in cooling degree days was associated with a 4.7 percent increase in reservoir visitation. Comparable statistical models are not available for projecting impacts on stream and river-based recreation (swimming, canoeing, kayaking, etc.). These activities would also be expected to be more popular as the summer season gets longer and mid-summer temperatures get higher. However, climate change is expected to change the timing of stream and river flows, with higher winter flows and lower summer and fall flows, when demand for stream and river recreation is highest.

12.6 Non-consumptive Forest Based Recreation

Non-consumptive forest-based recreation includes wildlife viewing, hiking, mountain biking, and camping. Climate change can impact participation in these activities either by affecting the forest and wildlife resource or by changing the demand for these activities.

As a consequence of climate change, forest species composition is expected to change. Currently, the dominant forest type in most of Pennsylvanian is maple/beech/birch, with oak/hickory dominating in southeast Pennsylvania. With climate change, some or all of the area currently in maple/beech/birch is expected to transition to the oak/hickory forest (Prasad et al 2007). Further, as detailed in Section 7, some forest land could be managed as plantation forests, though this is more of an issue for privately-owned forestland than for publicly owned land. These changes could make hiking and camping more or less attractive, though the direction is difficult to predict. Visits to forests for fall foliage viewing (leaf peeping) may decline, as the oak/hickory forest is typically considered less colorful than the maple/beech/birch forest (McNulty and Aber 2001).

While the NSRE indicates very high participation levels in wildlife and bird viewing, those statistics include wildlife and bird viewing at the home. The NSFHWAR measures participation in wildlife viewing away form the home. Table 12.5 summarizes

participation for several states. There is some evidence that participation is higher for Pennsylvania than for warmer states, particularly for days per resident.

State	Participation Rate	Days per participant	Days per resident
Pennsylvania	8.7 percent	12.3	1.1
Virginia	9.0 percent	8.3	0.7
North Carolina	4.3 percent	8.5	0.4
Georgia	3.6 percent	12.8	0.5

Table 12.5. Participation in wildlife viewing away from home. Source:NSFHWAR

Mendelsohn and Markowski (1999) estimated statistical models explaining variation among states in camping and wildlife viewing. They found that camping activity (total camping days) was positively associated with the amount of public forest, but there was not a clear association between camping activity and climate measures during the camping season. Wildlife viewing was found to be negatively related to summer temperatures in one of two models, but the relationship was not statistically significant in the other model. Therefore there is weak evidence that participation in wildlife viewing would be negatively affected by increased temperature associated with climate change.

12.7 Outdoor Recreation Not Associated with Natural Areas

Most outdoor recreation occurs close to home. This would include bicycling, walking, and outdoor sports such as golf, tennis and team sports. In Pennsylvania, an increase in temperatures due to climate change would lengthen the season for these activities. In the middle of summer, high temperatures may limit participation in these activities in the middle of the day, but participants can adjust the timing of their activities to take advantage of cooler morning and evening hours.

Scott and Jones (2006) found that golf participation around Toronto increased with daily high temperature up to 82 degrees F, was stable between 82 degrees F and 90 degrees F and declined with increasing high temperatures above 90 degrees F, probably due to discomfort at higher temperatures. They projected that golfing participation would increase as a result of climate change by 23-37 percent by 2020, and by 31-73 percent by 2080. Most of these increases are due to a lengthening of the golf season, rather than due to increases in rounds played per week. Because Pennsylvania is already warmer than Toronto, the impacts in Pennsylvania on golf participation are likely to be smaller. Similarly, Nicholls et al (2008) found that golf participation in Michigan was higher on days with higher maximum and minimum temperature, but they did not identify a threshold temperature above which participation declined. Mendelsohn and Markowski (1999) did not find a consistent relationship between golfing activity and temperature at the state level, but Loomis and Crespi (1999) did. They found that a 1 percent increase in average temperature resulted in a 1.9 percent increase in golfing days. While participation in other outdoor activities has not been studied as extensively as golf, similar changes in participation could be expected.

In addition to the enjoyment that participants receive, an important aspect of outdoor recreation is the health benefit from physical activity. Participation in outdoor activities that provide exercise is temperature sensitive. Participation is highest when the weather is dry with moderate temperatures (Merrill et al 2005). Lin et al (2007) found that residents of counties where the weather was more often suitable for outdoor exercise had lower body mass index (BMI), suggesting that the link between climate and exercise can be detected in health differences. They calculated an index of climate amenity equal to the percentage of off-work hours when the weather was suitable for outdoor exercise (between 23 and 85 degrees F and no severe weather) for each county in the U.S. Figure 12.1 shows the spatial pattern of their weather amenity index. They found that average BMI was highest for residents of counties with low weather amenity, and lowest for residents of counties with high weather amenity. For Pennsylvania, a small increase in temperature (2.5 degrees C) would make the climate more like that of Virginia, and would increase the weather amenity index, while a larger temperature increase (5 degrees C) would start to decrease the weather amenity index because of excess heat.

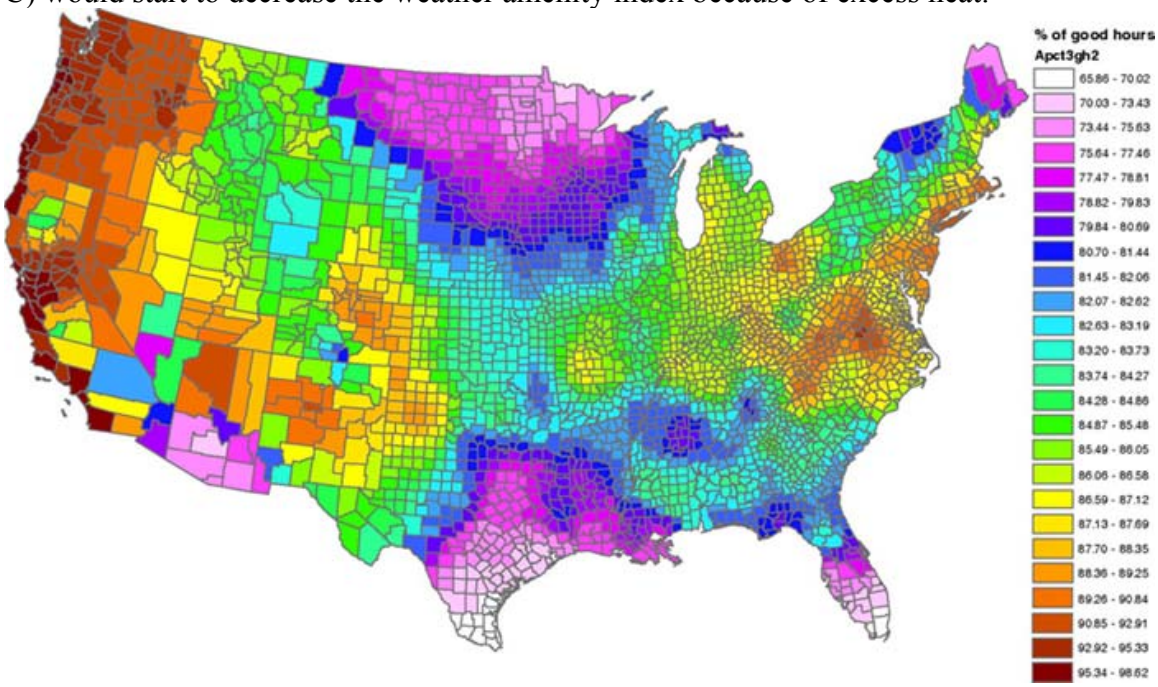

Figure 12.1. Weather Amenity Index for Outdoor Exercise. Source: Lin et al 2007.

The analysis of Lin et al focused on working adults, and did not include daytime temperatures. Increased high temperatures on the afternoons of hot summer days could limit outdoor activities for school children.

12.8 Outdoor Recreation Tourism

Previous sections discussing hunting and fishing included some information about participation in these recreational activities in Pennsylvania by out of state residents. However, those two categories constitute a minority of the tourist visits to Pennsylvania for outdoor recreation. According to a study conducted for the Pennsylvania DCNR

(D.K. Shifflet and Assoc 1998) 15.9 million travelers visited Pennsylvania in 1997 for the purpose of outdoor recreation. This constituted 14 percent of all visits to the state. The most common activities engaged in by out of state visitors were nature/sightseeing (20 percent), camping (19 percent), hiking (9 percent), hunting and fishing (6 percent) and rafting/boating/canoeing (6 percent). The part of the state most commonly visited for outdoor recreation was The Hershey/Pennsylvania Dutch region, followed by the Poconos.

These visitors spent $4 billion dollars, which in turn generated an additional $3.9 billion in indirect and induced economic activity. This economic activity supported 106,000 jobs, and generated $2 billion in earnings for Pennsylvania residents and $1.07 billion in tax revenues.

Visitation to the state for outdoor recreation has a sharply seasonal pattern, as shown in Figure 12.2. . Of the total visitation, 51 percent occurred during the summer months (June, July and August), 17 percent occurred during April and May, and 17 percent occurred during September and October. The five coldest months (November through March) accounted for only 15 percent of all out of state visits for outdoor recreation. This seasonal pattern suggests that summer recreation activities dominate winter activities for out of state tourists. An increase in temperatures as a result of climate change might therefore increase out of state tourism for outdoor recreation, particularly tourism from nearby warmer regions such as the Baltimore/Washington area.

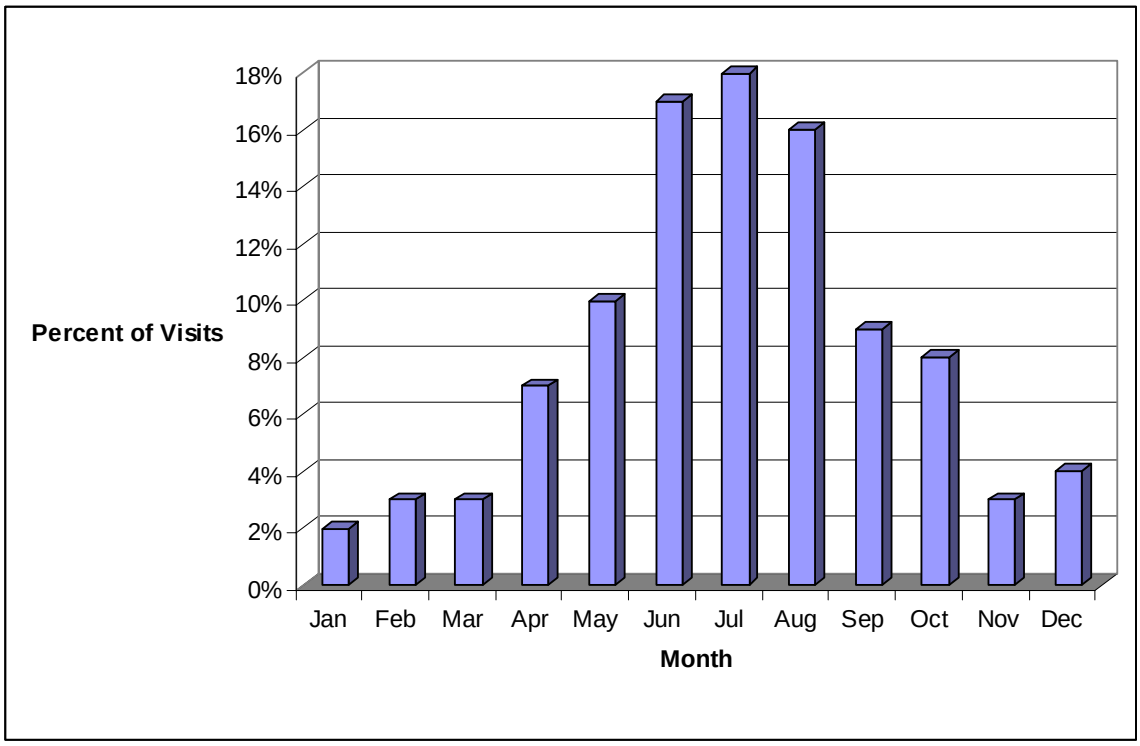

Figure 12.2. Timing of out of state visits for outdoor recreation (source: D.K. Shifflet & Assoc. 1998)

Currently, summer temperatures in Pennsylvania are moderate enough to encourage tourism. A large increase in summer temperatures could make Pennsylvania, particularly Southeastern Pennsylvania, less attractive as a summer destination due to high heat. Scott et al (2004) projects that the seasonality of Pennsylvania's tourism season could shift to a bimodal pattern, where Pennsylvania's climate is best suited to tourism in late spring and early fall. That does not mean that visitation will peak then, however. Families may be constrained by school schedules from increasing their tourism activities during the shoulder seasons.

12.9 Adaptation Opportunities

Changes in the Pennsylvania climate will have negative impacts for some activities (notably winter sports and trout fishing) and positive impacts for other activities (warm-water fishing, swimming and boating, golf, and outdoor exercise). Adaptation options include those aimed at minimizing negative impacts and those aimed at capitalizing on new opportunities.

There are few options available to sustain cross country skiing and snowmobiling. These activities rely on natural snow, which will decrease as a result of climate change. For downhill skiing, it is possible to somewhat offset warmer temperatures and decreased snowfall with increased expenditures on snowmaking. These cost money and use energy. Resorts should be encouraged to replace older, less efficient snowmaking equipment with newer, more efficient equipment that can make snow more quickly to capitalize on shorter periods with cold temperatures.

Increased temperatures will reduce the number of stream stretches that can support wild trout populations. Where wild populations are no longer viable, trout stocking could replace natural productivity to some extent, though the Pennsylvania Fish and Boat Commission faces facility constraints and is currently producing as much trout as possible at its hatcheries. Some waters that currently support stocked trout will become too warm. Most of these waters will transition to warm-water fish habitat. Further, waters will warm earlier as a consequence of climate change. The timing of fishing seasons may need to be adjusted. This does not necessarily mean that fishing activity will decline. The evidence is that anglers are adaptable and will switch species. In fact, total demand for fishing days will most likely increase as a consequence of climate change. The Fish and Boat Commission should consider this increase when planning its programs to provide anglers access to streams and lakes.

Warmer summer temperatures and a longer summer season will increase demand for water-based recreation other than fishing. Pennsylvania is well positioned to accommodate increased demand for river and stream-based recreation. As measured by the number of stream miles per square mile of land area, Pennsylvania has a 70 percent higher stream density than the average for the continental United States. In contrast, Pennsylvania has a relatively low density of lakes and reservoirs. Water makes up 2.6 percent of Pennsylvania's area, compared to an average of 5.2 percent for the entire continental United States. On a per capita basis, Pennsylvania waters are even more

scarce. Pennsylvania has an average of 0.1 square miles of surface water area per 1,000 residents, compared to 0.6 square miles on average for the entire continental United States.

The state could capitalize on the increased demand for water based recreation by developing new access points to existing streams, rivers and lakes, or by constructing new reservoirs. In addition to reducing crowding caused by increased demand due to higher temperatures, construction of new reservoirs could itself stimulate additional demand for reservoir-based recreation. There is clear evidence that participation in swimming and boating at reservoirs is higher in areas that have more and larger reservoirs (Mendelsohn and Markowski 1999; Ward et al 1995). Further, reservoirs could help reduce flooding and maintain summer in-stream flows, thus partially offsetting some of the potential impacts of climate change on hydrology. At the same time, dams flood streambeds and terrestrial ecosystems, block fish passage, and are potentially dangerous to swimmers and boaters. If reservoirs were to be constructed, care would need to be taken that they would not adversely impact other recreational or environmental resources such as canoeing and kayaking streams or coldwater fishing streams.

Finally, a longer warm season will encourage residents to spend more time in outdoor sporting and exercise activities. Local communities should plan for this increase in demand for sports fields, bicycle paths, etc. Ancillary benefits of building additional sports fields and bicycle paths are an improvement in public health and an increase in the proportion of the population that walks or bicycles to work or school (Nelson and Allen 1997) and a consequent decrease in traffic and motor vehicle emissions.

It should be noted that an increase (decrease) in an activity as a result of climate change does not necessarily mean that people who engage in that activity have been made better off (worse off) by climate change. In some cases, the linkage is fairly clear. A decrease in skiing due to decreased snow means that skiers have been made worse off. In other cases, however, the change in participation could signal a shift from a preferred activity to a less-preferred activity. For example, an increase in water-based recreation associated with higher temperatures does not necessarily mean that all swimmers have been made better off by higher temperatures. Some may be substituting away from an activity they prefer, such as hiking or tennis that has been made less enjoyable because of the heat.

12.10 Mitigation Barriers and Opportunities

Outdoor recreation is not a major source of GHG emissions. For most outdoor recreation activities, the most important component of GHG emissions is associated with travel to and from recreation sites. Providing recreation opportunities closer to populated areas would reduce the travel distance for each recreation trip, but could stimulate more participation, and therefore more trips. A smaller contribution to GHG emissions is energy use during recreation (for example to power boats and ATV's).

An exception to the above generalization is downhill skiing, which relies on snowmaking, which requires energy. Statistics on CO2 emissions are not available for

Pennsylvania resorts. One estimate that is available is for Sunday River resort in Maine, which emits 0.019 tons of CO2 per skier visit (Scott 2006). The average for a Pennsylvania resort is likely higher. To put this into perspective, that is about equivalent to the carbon emissions per person from driving a typical car a distance of 34 miles. So, if a skier drives 17 miles each way to the ski resort, the emissions from their driving will be equal to the average emissions from the snowmaking done to support their skiing. Still, because snowmaking is a centralized activity, it provides an opportunity for emissions reductions. Newer snowmaking technology is more energy efficient, and allows resorts to make snow at warmer temperatures.

12.11 Information Needs

The impact of climate change on outdoor recreation occurs through two pathways. First, climate change can affect the quality of the recreation resource. Examples include changes in the distribution of cold-water fish species due to warming. Second, climate change can affect the choices made by recreationists. Examples include decisions to go to the beach at a reservoir instead of going for a hike in the woods, because of high temperatures. Research is needed on both pathways, both to predict the impacts from climate change and to anticipate those impacts and adapt to them.

The largest uncertainties regarding climate change impacts on the quality of recreation resources are for fishing. Better information is needed on the potential impacts of climate change on fish habitat. In particular, research is needed on which stream segments will no longer be able to support wild trout populations, and which stream segments will no longer be suitable for trout stocking. Further, research is needed on the impact of potential low summer flows on both cold-water and warm-water fisheries. This research is needed both to assess the potential impact that climate change will have on fishing, and to manage the fisheries adaptively as climate changes. Similarly, research is also needed on the impact of climate change on the distribution and abundance of game wildlife species, though the impacts of climate change on important game species are expected to be smaller than those on fish species.

Equally important is uncertainty over preferences and behavior of recreationists. In particular, research is needed on what types of recreation experiences Pennsylvania residents and tourists seek, and how their enjoyment would be affected by climate change. For example, research is needed to determine whether a shift from cold-water to warm-water fishing would result in a change in fishing enjoyment for anglers, and how that change might vary among anglers. This research could include surveys of anglers or revealed preference approaches that rely on observed angler behavior. As another example, research is needed to determine the demand for water-based recreation, and whether that demand is currently being adequately served by available resources, or will be adequately served in the future when demand is expected to increase due to a longer summer season and higher maximum temperatures. As a third example, research is needed on how changes to forest composition and structure would affect forest-based recreation such as hiking, mountain biking, and camping.

When researching the demand for outdoor recreation, and how that demand might change, it is important to take a regional perspective. Climate change may make Pennsylvania a more attractive recreation destination, particularly for tourists from neighboring states to the south.

12.12 Conclusions

Changes in the Pennsylvania climate will have negative impacts for some activities (notably winter sports and trout fishing) and positive impacts for other activities (warm-water fishing, swimming and boating, golf, and outdoor exercise). Adaptation options include those aimed at minimizing negative impacts and those aimed at capitalizing on new opportunities.

The outdoor recreation activities that will be most severely impacted are snow- and ice-based recreation such as skiing, snowmobiling and ice skating and fishing. There is very high confidence in the direction of these impacts. Downhill ski resorts can partially adapt to higher temperatures by increasing their use of snowmaking during the (now shorter) cold periods. Newer snowmaking equipment is more efficient and can make snow at slightly warmer temperatures. Increased snowmaking is expensive and uses energy, however. Projections for Pennsylvania are that, even with increased snowmaking, ski season length will decrease by 46-50 percent by the end of the century. It is questionable whether resorts will be economically viable with such short seasons.

Dispersed snow-based recreation such as cross country skiing and snowmobiling are at even more risk. Pennsylvania's climate is already marginal for these activities. As a consequence of warming and less snowfall, the number of days when conditions are suitable for cross country skiing or snowmobiling in Pennsylvania is projected to decrease by 60-90 percent in north-central Pennsylvania, and by 75-90 percent in eastern Pennsylvania. Because snowmaking is not practical, there are few adaptation opportunities for these activities

Increased temperatures will reduce the number of stream stretches that can support wild trout populations. The direction of this impact is established with high confidence, though the magnitude of the impact is uncertain. Increased stocking can serve as a partial substitute for lost wild trout habitat, but some waters will become too warm to support even stocked trout. A reduction in the availability of cold-water fishing does not mean that fishing activity will decline, however. In fact, the evidence is that total demand for fishing days will most likely increase, due to a longer season with pleasant weather and due to a desire to be near water on hot days. The direction of this impact is established with medium confidence. The Fish and Boat Commission should consider this possible increase in warm-water fishing activity when planning its programs to provide anglers access to streams and lakes.

It is difficult to project whether climate change would have either a positive or a negative impact on hunting participation. The most important game species in Pennsylvania are fairly widely distributed, and tolerant of different climates. Changes in forest composition

could affect wildlife abundance, but the direction the impact is difficult to predict. Similarly, changes in weather could affect hunter behavior, but again the direction of the impact is difficult to predict. Likewise, participation in non-consumptive forest-based recreation such as hiking and camping could be affected by climate change. Higher temperatures will lengthen the season for such activities, but could make them less enjoyable in the middle of summer. Changes in forest composition could also affect these activities. The direction that climate change might impact these activities cannot be established.

Warmer summer temperatures and a longer summer season will increase demand for water-based recreation other than fishing, such as swimming and boating. There is high confidence in the direction of this impact. The state could capitalize on this increased demand by providing more opportunities for water-based recreation in the form of new stream access points and reservoirs

Finally, a longer warm season will encourage residents to spend more time in outdoor sporting and exercise activities such as golf, tennis and biking. There is high confidence in the direction of this impact. For example, studies have consistently shown that golf participation is positively related with temperature, due mostly to a longer golfing season. The same effect would be expected for other outdoor sports. Local communities should plan for this increase in demand for sports fields, bicycle paths, etc.

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13.0 Insurance and Economic Risk

The previous sections have made clear the potential economic and ecosystem impacts of climate change. The insurance industry is no different. As stakeholders in these other industries have taken note of the potential impacts of climate change, so has the insurance industry. Indeed, some companies have named climate change as one of the biggest challenges facing the insurance industry. Ernst and Young have stated that climate change is a "long-term issue with broad-reaching implications that will significantly impact the industry" (Hecht 2008, p. 1561). John Coomber, former CEO of Swiss Re, a large reinsurer, has named climate change as "the number one risk in the world ahead of terrorism, demographic change and other global risk scenarios" (Kunreuther and Michel-Kerjan 2007, p. 3). Insurers play a vital risk-spreading role in the marketplace. Given the potential within the insurance industry for increased risk exposure as a result of climate change, insurers worldwide are likely to become more vulnerable in coming decades in the absence of climate change mitigation efforts.

13.1 Climate Change and Insurance

The primary vehicle through which climate change may affect the insurance industry is through increased weather related losses to property and casualty insurers. Globally, the past several decades have seen significant increases in the frequency of severe weather-related events as well as the economic losses caused by these events. Weather-related natural disasters caused $1.4 trillion dollars in losses from 1980 to 2004 globally (Mills 2005). The period from 1990 to 2005 saw 18 of the 20 most costly weather-related insurance loss events (Kunreuther 2006). Prior to 1990, insurance losses due to weather-related events were comparatively small. In 1989, Hurricane Hugo became the first natural disaster to exceed the $1 billion dollar insured loss threshold. Since, losses have skyrocketed. Hurricane Andrew in 1992 and the 1994 Northridge, Calif. earthquake, with respective losses of $22.3 billion and $18.5 billion, led to questions among insurers about whether such risks were indeed insurable. The years 1991, 1992, and 1994 each saw insured losses exceeding $15 billion. In 2004, losses reached $120 billion (Kunreuther and Michel-Kerjan 2007). In the U.S., hurricanes have caused the largest insured losses. Exemplifying this pattern, six hurricanes hitting the Florida and Gulf coasts in 2004 and 2005 "comprised half of the top 12 disasters with respect to insured losses between 1970 and 2005" (Kunreuther 2006, p. 2).

Accurately pricing insurance risks depends upon the ability of insurers to quantify and predict average losses. In so doing, insurers can price policies according to the risks they face. Ideally, from an insurance perspective, exposure to losses should also be uncorrelated across insured parties such that insurers are not exposed to large losses from single events (Hecht 2008). However, extreme weather events such as hurricanes and floods fail to adhere to these criteria. They remain highly unpredictable and losses tend to be geographically concentrated.

As noted earlier in this report, there are high levels of uncertainty regarding the impacts of climate change on severe weather events (see sections #4, #5). Despite the increases in

insured losses due to severe weather events, there is still debate as to whether increases in severe weather events can be attributed to climate change. Some contend that the increased activity of the past few decades reflects anthropogenic climate change and predict more of the same in the future, while others cite similar weather patterns in the historical record and contend that climate change has not had an effect. For instance, the National Oceanic and Atmospheric Administration has attributed increased tropical cyclone frequency to the Atlantic Multidecadal Oscillation, a cyclical warming and cooling of sea surface temperatures. Despite this warming trend, hurricane activity remained highly variable, with no hurricanes making landfall during several years in the last decade. Recent IPCC reports convey this uncertainty in stating that "it is likely that future tropical cyclones will become more intense...there is less confidence in projections of a global decrease in numbers of tropical cyclones" (Guin 2008, pp. 5-6). As a result of this uncertainty, we can only use current research to project how climate change might impact severe weather events, and, in turn, the insurance industry.

The key questions for insurance companies in Pennsylvania are whether they will face increased weather-related insurance risks; which, if any, of these risks can be accurately predicted; and which risks insurers can price accurately. Homeowners and property coverage constitute the major areas of exposure among Pennsylvania insurers. The four largest property insurers in the state are Erie Insurance Exchange, State Farm, Allstate, and Nationwide. In total, there were about $20 billion in direct premiums written in 2007 among property writing companies (Pennsylvania Insurance Department 2008). Health and life insurance risks may be affected as well.

13.2 Climate Change and Weather-Related Losses in Pennsylvania

There are several weather-related property and casualty losses that could be affected by climate change, including hurricanes, floods, ice storms, freezing rain, and wildfires. Of course, flooding often accompanies hurricanes.

13.2.1 Hurricanes and Floods

Historically, hurricanes have caused the largest insured losses in the U.S. Their unpredictable nature and their tendency to concentrate large losses in certain areas can create threats to the solvency of insurance carriers and reinsurance providers. Though hurricanes have caused insurance losses in Pennsylvania, the bulk of hurricane losses have occurred in high-risk coastal communities along the Gulf of Mexico and Atlantic coast. There is the possibility that a severe storm could hit the state, but the severity and frequency of hurricanes remain highly uncertain. This high degree of uncertainty makes hurricanes a non-priceable risk in the context of the Pennsylvania insurance market. However, it can be said that Pennsylvania insurance companies are in a comparatively safe position at the present time, especially relative to U.S. states with significant coastlines such as Florida and Texas.

Flooding does not directly impact insurance companies because it is not covered under standard homeowner's or commercial property insurance policies. Insurance is available

through the National Flood Insurance Program (NFIP) for those living in flood plains in which the local government has implemented a floodplain management ordinance. However, flood insurance remains very expensive, with costs of flood insurance potentially doubling the costs of a traditional homeowner's policy. As a result, people tend to buy flood insurance only when they perceive it as necessary. According to NFIP, there are 67,380 flood policies in Pennsylvania out of 4.8 million households, amounting to only 1.4 percent of households (NFIP 2007). The state ranks twelfth in the number of flood insurance policies in effect. Despite the small percentage of flood insurance policies written, "approximately 25 percent of all flood damages occur in low-to-moderate risk areas" (Pennsylvania Department of Insurance 2008).

Although the insurance industry may not be directly affected by flood losses, these losses can still be substantial for homeowners and businesses. According to FEMA, Pennsylvania suffered more than 15 flood-related federally declared disasters in the years 1997 to 2006. From 1955 to 2003, economic losses from flooding totaled $16 billion, with the state ranking fourth in flood losses ("Flood Damage" 2003; "Flood Safety" 2008). From 2002 to 2006, there were $337 million in insured losses as a result of flooding (NFIP 2007).

The climate projections in this report suggest that Pennsylvania may see an increase in average precipitation, especially during the winter months. A recent study of the Mid-Atlantic region found that a 1 percent increase in annual precipitation could lead to as much as a 2.8 percent increase in catastrophic losses from flooding (Choi and Fisher 2003). In 2008, the Pennsylvania Emergency Management Agency projected that a 10-year flood would inflict about $9 billion in damages to residential and commercial buildings in the nine Pennsylvania counties with the largest populations. They projected that a 50-year flood would cause approximately $12 billion in damages (Pennsylvania Emergency Management Agency 2008). Using Choi and Fisher's analysis, this implies that a 1 percent increase in average precipitation could increase the 10- and 50-year flood losses by about $250 million and $330 million, respectively.

On the other hand, flooding in winter and spring months is primarily a function of when snow melt occurs and how quickly it occurs (see section #6). The projections in this report suggest that climate change will lead to less snow cover during winter months (see section #5), which should lower flood risks. The net effect on flooding is uncertain.

Though unlikely, it is important to consider what would occur if Pennsylvania was faced with an event such as a catastrophic hurricane or massive flood. Such an event could expose Pennsylvania insurers to massive losses in excess of receipts from premiums. However, property and casualty insurers are insulated by high levels of surplus funds. In this respect, large insurers are more protected against insolvency than small insurers. Should insurers face insolvency, Pennsylvania has a public contingency fund in place to protect policyholders. The Pennsylvania Property & Casualty Insurance Guaranty Association (PP&CIGA) assumes the insurance liabilities of any licensed insurers declared insolvent in the state. Though not all losses are covered, PP&CIGA does provide a layer of protection for policyholders (PP&CIGA 2009).

Another possible concern is that large weather-related losses in another state would affect the financial health of Pennsylvania insurance carriers also operating in those states. However, to remain competitive, insurance companies work to avoid overexposure in any one area. Any attempts to pass on weather-related losses in other states to Pennsylvania insurance customers would likely be blocked by Pennsylvania insurance regulators and competitive pressures from other carriers not affected by the losses in other states.

13.2.2 Ice Storms and Freezing Rain

Ice storms and freezing rain pose another risk to Pennsylvania insurers. Freezing rain and ice can lead to hazardous driving conditions and significant damage to buildings, communication towers, and electrical wires (Cheng et al. 2007). According to a Penn DOT study, snow, sleet and freezing rain conditions caused 4,404 accidents and 38 deaths in Pennsylvania in 2006. It is important for insurance companies to understand the risks associated with freezing rain as well as future changes in the frequency and intensity of such events as a result of climate change (Changnon and Bigley 2005).

There is little research on the impacts of climate change on freezing rain events. This is partially because freezing rain is very difficult to study as it only occurs under very specific surface and atmospheric conditions (Cheng et al. 2007). It often occurs in very narrow bands and is subject to high degrees of variance even at relatively small geographic scales. According to one regional study, Pennsylvania currently falls in the high-incidence category, with the most freezing rain events occurring in the north, less in central and southeastern parts of the state, and even less in southwestern Pennsylvania (Changnon and Bigley 2005).

Cheng et al. (2007) studied the impacts of climate change on the number of freezing rain events in Ontario, Canada. For winter months (December-February), they projected increases by 2050 of 85 percent, 60 percent, and 40 percent in freezing rain events in northern, eastern, and southern Ontario respectively. By 2080, these percentages were projected to increase to 135 percent, 95 percent, and 45 percent. The study also predicted decreases of 10 percent and 15 percent in freezing rain events for southern Ontario in 2050 and 2080 respectively for the fall and spring months of November, March, and April (2007). It is very difficult to take results for Ontario and extrapolate them to Pennsylvania (see section #5), although northern Pennsylvania is 50-100 miles south of southern Ontario. If freezing rain events decline in the fall and spring in southern Ontario, it seems likely that they would decline in Pennsylvania as well. An increase in freezing rain events in the winter in southern Ontario might or might not be matched in Pennsylvania.

Several studies have analyzed changes in the frequency and intensity of extratropical winter cyclones, which are the primary vehicle for severe winter weather in the northern midlatitudes (Teng et al. 2008). Lambert and Fyfe (2006) studied global patterns in such storms utilizing GCM runs of the IPCC's B1, A1B, and A2 scenarios. All the climate models found a decrease in the total number of events along with an increase in the

intensity of events that did occur (Lambert and Fyfe 2006). Other studies have reached similar conclusions. In an analysis of North America, Teng et al. (2008) found that the frequency of wintertime extratropical cyclones decreased on the East Coast, though these results are based upon only one GCM realization. A model run including eight more realizations also suggested reductions in cyclone frequency, albeit with greater uncertainty (Teng et al. 2008). These results suggest that the impact of climate change on freezing rain-related insurance losses in Pennsylvania is highly uncertain.

13.2.3 Wildfires

Wildfires pose another climate change-related risk for insurers, though historically such losses in Pennsylvania have been small. There is little research on wildfire risks and climate change for the eastern U.S. but there are several studies for other regions. In a regional study focusing on Northern California, researchers found that climate change would likely increase both the frequency and intensity of wildfires (Fried, Torn, and Mills 2004). In a similar study focusing on Canadian and Russian boreal forests, it was found that "all models show a significant increase in the area under high to extreme fire danger" as a result of doubling of CO_2 levels (Stocks et al. 1998, pg. 5).

It is difficult to apply these results to Pennsylvania but it is possible that Pennsylvania may be at increased risk for wildfires. As noted in the forestry section of this report (see section #7), Pennsylvania's forests are likely to undergo significant changes as a result of climate change. Higher temperatures and a greater frequency of droughts, combined with dying trees, may lead to more wildfires in the state. As a result, insurers may need to incorporate changes in wildfire risk into their pricing calculations. Additional research on climate change and wildfire risks in Pennsylvania would help insurance companies in pricing these risks. It would also aid homeowners and businesses in making building decisions, and state and local governments in designing building codes.

13.3 Adaptation Options

Pennsylvania insurers are in a comparatively good position relative to insurers in other states with respect to weather-related insurance risks, but there are still a number of adaptation and mitigation options that insurance companies may wish to address. Because of the insurance industry's position as a risk-spreading institution, it is uniquely positioned to help to manage changing risk exposures as a result of climate change (Hecht 2008). Furthermore, since insurers cover many industries that emit significant quantities of greenhouse gases, their policies can potentially influence the emissions decisions of these industries (NAIC 2008).

Households, businesses, insurance companies, reinsurers, rating agencies, and government agencies can all take steps to adapt to changes in property and casualty risks created by climate change. For insurers, the most straightforward adaptation option is to price policies according to risk exposure. If insurers perceive higher risk levels as a result of climate change, they should price their policies accordingly (Hecht 2008). Insurers can also adjust other terms of coverage such as coverage limits and deductibles, and may

even choose to stop writing certain types of policies. All of these adaption options send a signal to policyholders about their risk levels and provide an incentive to policyholders to take their own measures to adapt.

In order for insurers to adapt, they need information on how climate change will impact their risk exposures. This may require insurers to invest in research on the potential impacts of climate change on their industry. Some insurers have begun to address the issue of climate change but many have not. Companies can begin to integrate climate change projections into their pricing models by reaching out, and collaborating with, natural scientists working on climate projections (Vellinga and Mills 2001). In addition, companies can engage in consumer education to make policyholders more aware of the risks they currently face and how climate change could alter those risks (NAIC 2008).

Households and businesses can influence their own risk levels through their building and location decisions. Though Pennsylvania is not currently at a high risk for weather-related catastrophes, households and businesses can reduce their exposure to these low probability events by making informed decisions. This includes avoiding construction in flood plains and in areas with a high risk of wildfires. State and local governments can engage in research to help improve land use planning and regulation.

Property owners can renovate existing properties with more weather-resistant materials. This is particularly important after disasters when property owners needing to rebuild anyway can rebuild in more weather-resistant ways (Vellinga and Mills 2001). Insurers can aid this process by giving rate reductions for weather-resistant retrofitting or rebuilding. Insurers can learn about the effectiveness of community building codes through ISO's Building Code Effectiveness Grading Schedule (ISO). State and local governments can directly promote stronger building codes through increased regulation and enforcement. In July 2004, Pennsylvania enacted a uniform building code establishing minimum building code standards for communities. The next month, a tornado in Campbelltown destroyed 300 homes. When these homes were rebuilt, they had to adhere to the new building code standards. Though this can increase costs initially, it reduces the risk that losses of this scale will occur again.

As discussed in the agriculture section of this report (see section #9), an increase in the variability of temperature and precipitation is likely to increase the demand by farmers for risk management products. Agricultural producers currently have a range of federally subsidized risk management products from which to choose, including yield insurance against losses due to natural causes such as drought, excessive moisture, hail, wind, frost, insects, and disease; catastrophic loss insurance; gross revenue insurance that protects against gross revenue falling below a specified level; and adjusted gross revenue insurance that insures the revenue of an entire farm rather than a specific crop.

Other adaptation options involve reducing the financial impacts of weather-related insurance losses once they have occurred. These options attempt to spread risk so that insurance companies, policyholders, and regulators can efficiently adapt and deal with the impacts of natural disasters (Hecht 2008). Reinsurance markets are the primary risk-

spreading vehicle. In acting as insurers for insurance companies, the reinsurance industry takes on the portion of risk in excess of what the insurer is willing to bear alone. Pennsylvania is currently not a large market for reinsurers, particularly relative to insurance markets that face much larger risks. For instance, in Louisiana reinsurers took about half of the losses from Hurricane Katrina (Kunreuther and Michel-Kerjan 2007).

In addition to reinsurance, financial markets have created instruments fulfilling a function similar to reinsurance. Weather derivatives allow businesses to hedge against weather-related risks in industries such as energy and agriculture. Unlike insurance against bad weather, which typically covers high-risk, low-probability events, weather derivatives typically cover low-risk, high probability events. Catastrophe bonds are another instrument utilized by insurance companies. If an insurer encounters a weather-related loss in excess of what was established on the bond, the insurer does not have to repay the principal on the bond. Such investments can be attractive in the absence of adequate levels of reinsurance (Kunreuther and Michel-Kerjan 2007). Adequate reserves and insurer contingency funds can also ensure insurer solvency in the event of a weather disaster.

Government can also serve as a risk-spreading institution. Governments can operate insurance and reinsurance programs in the event that the private insurance market is unable or unwilling to provide certain coverages, such as flood insurance. Regulators can also impose rate and coverage regulations. However, the government should avoid distorting insurance markets by subsidizing insurance to the point that it no longer accurately reflects risk levels (Kunreuther 2006), or by imposing rate caps that make it unprofitable to provide insurance. Regulators can also help to ensure insurer solvency through reserve requirements and contingency funds such as PP&CIGA. Finally, governments can provide financial incentives to insurers engaging in risk adaptation activities (NAIC 2008).

Though it is unlikely that a catastrophic weather event will occur in Pennsylvania, insurers need to be adequately protected should such an event occur. Rating agencies can aid in this process by including catastrophe exposure as a factor influencing ratings (Kunreuther and Michel-Kerjan 2007). Rating agencies and government regulatory agencies can require greater disclosure from insurers regarding their climate change exposure and what they are doing to manage these risks. Current SEC regulations are ineffective in obtaining such disclosure from insurers (NAIC 2008). In some cases investors are pressing publicly owned insurance companies for more climate change-related disclosure. In response to emerging climate change risks, the NAIC mandated in March 2009 that insurers begin to issue reports disclosing their exposure to climate change risks beginning in 2010 (Ball 2009).

In the end, the goal of adaptation options is to enable insurers, regulators, policyholders and other interested parties to understand and manage risk exposures more effectively. If all parties are made aware of the climate change-related risks that they face, the results can benefit everyone involved. For example, if households and businesses avoid building in high-risk areas, insurance companies benefit from lower and more predictable risks.

Government expenditures on programs such as NFIP benefit as well, and regulatory agencies benefit from a lower risk of insurer insolvency.

13.4 Mitigation Barriers and Opportunities

While climate change does not threaten Pennsylvania's insurers to the degree that it does insurers in higher risk areas, insurance companies operating in Pennsylvania will still benefit from reductions in greenhouse gas emissions. This creates an incentive for insurers to implement new policies that help in climate change mitigation. However, this is only to the extent that these policies also reduce risk exposures for insurance companies. There is little incentive for insurance companies to offer such policies if reduced emissions are not correlated with risk reductions (Hecht 2008). Climate change also presents new investment opportunities for insurers. In addition to helping the environment, mitigation activities can improve the corporate image of participating companies.

Green products are a potential opportunity for insurers. Insurers have begun to offer rate reductions for policyholders utilizing such products. AIG offers up to a 10 percent rate reductions for new pollution legal liability insurance for LEED (Leadership in Energy and Environmental Design) certified properties. They also provide property coverage that enables policyholders to rebuild using green products after suffering a loss (AIG 2007). Similarly, Fireman's Fund offers 5 percent rate reductions for green products such as solar panels, green roofs, and recycled water supply systems (Kunreuther and Michel-Kerjan 2007).

The auto insurance industry has become involved in the "greening" of insurance. Some auto insurers have begun to offer rate reductions for policyholders driving energy efficient hybrid vehicles. Another relatively new possibility is pay-as-you-drive (PAYD) auto insurance. Such policies would provide the incentive to reduce miles driven, thus combining environmentally friendly practices with risk reduction. The EPA estimates that a 10 percent reduction in miles driven, approximately the reduction expected from such policies, would reduce greenhouse gas emissions of 4.5 billion CO_2-equivalent tons. However, insurers have been hesitant to implement PAYD policies because it is not clear if driving fewer miles is correlated with risk reductions (Hecht 2008). For example, one can drive hundreds of miles on a rural interstate highway at virtually no risk of an accident or a few miles in congested urban traffic at a much higher risk.

In general, these policies should be undertaken with actuarially-based pricing principles in mind. A recent AIG brochure states that the company "sees opportunity to improve the environment, protect customers and reward shareholders by developing products and investing in technologies that can mitigate the risk and the effect of climate change" (AIG 2007). This statement illustrates that even though environmentally friendly behavior is important to AIG, any mitigation oriented policies must also serve their business and profitability concerns. If these products reduce insured losses, we can expect them to become more commonplace (Hecht 2008). If they do not, it is unlikely that insurance companies will continue to offer them.

If alternative energy industry grows as a result of climate change mitigation policies, its insurance needs will grow as well. This represents an opportunity for insurance companies to engage in environmentally friendly practices while opening new lines of business. Insurance companies can help facilitate the innovation and implementation of alternative energy technologies by helping to manage the risk that inevitably accompanies such ventures (Hecht 2008). If a carbon cap-and-trade scheme is adopted, carbon trading markets would represent another investment opportunity for insurers. Carbon capture and storage represents a possible opportunity for insurers, provided the associated risks can be priced accurately and there is a willingness to purchase insurance at those prices.

13.5 Health and Life Insurance

The impacts of climate change can extend beyond property and casualty insurance to health and life insurance risks. Health insurers can be impacted through catastrophes. For example, Hurricane Katrina led to significant bacteria and chemical exposure among victims. As the section of this report on human health indicates, potential impacts can also arise from heat waves, water pollution, vector borne diseases, particulate matter, and allergens, among others. However, the potential impacts of climate change on human health are not fully known or understood (NAIC 2008). Furthermore, it may be difficult to attribute changes in human health to climate change amid the many other factors that affect health. Similarly, it may be difficult for life insurance companies to disentangle the effects of climate change on mortality from all the other factors affecting life expectancy. Over time, however, any changes in mortality that do occur will become part of the actuarial tables used to price life insurance products.

Compared to states such as Florida and Texas, Pennsylvania is in a comparatively safe position in regard to natural hazards. Health and life insurance companies can facilitate adaptation to climate change by educating consumers about appropriate responses to severe weather events.

13.6 Information Needs

This section has discussed potential risks facing insurers in Pennsylvania due to climate change, including hurricanes, floods, ice storms, freezing rain and wildfires. However, we have seen that these projections remain highly uncertain. Thus, it is difficult for the insurance industry to accurately project how their risk exposures may change in the future due to climate change. There is a need for continuing research and collaboration between the insurance industry and climate scientists.

It is very difficult, or impossible, to generalize projections for weather events from other regions to Pennsylvania. Filling this information gap will require regional studies focusing specifically on Pennsylvania or on them mid-Atlantic region. Research is needed for all weather-related events relevant to the insurance industry including hurricanes, floods (particularly rain on snow flood events), wildfires, and ice storms.

Such information can help insurers accurately price policies while also informing future regulations and appropriate adaptation options.

13.7 Conclusions

Though climate change carries the potential to exacerbate the risks of weather-related losses for the insurance industry, Pennsylvania's insurers are less exposed to such risks than insurers in many other states. The available evidence does not permit us to say anything definitive about the effects of climate change on hurricane and flood risks. Ice storms and freezing rain may become less prevalent in the fall and spring, but it is unclear whether such events will be more or less prevalent during the winter. Pennsylvania may be at increased risk for wildfires, but it is unclear as to how large the increase in risk might be.

Effective regulatory management of the insurance industry that fosters competition will continue to protect Pennsylvania's citizens from insurer insolvency. Insurers should continue to price policies according to risk, and they should remain vigilant in evaluating their risks. Insurers can collaborate with climate scientists and make efforts to integrate climate change into their pricing decisions. Insurers can also educate policyholders about how climate change might affect the risks facing them. Other adaptation options include land use regulation and decision-making with climate change in mind, improved building codes, reinsurance, and other risk-spreading financial instruments.

Insurance companies should be aware of opportunities to combine environmentally friendly practices with reduced loss exposures. Such mitigation activities include rate reductions for green products and insurance products for the alternative energy industry. It is vital that the stakeholders in Pennsylvania's insurance industry act and adapt to climate change while recognizing the significant uncertainties surrounding this issue. As knowledge about climate change improves, the insurance industry in Pennsylvania will need to adapt to ensure its future vitality.

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14.0 Economic Barriers and Opportunities

This report has identified a number of opportunities for adaptation to climate change in Pennsylvania, and also related to climate change mitigation in Pennsylvania. Some of these opportunities are *economic*, and hold the potential to create new jobs or industries in Pennsylvania. Others are *policy-oriented*, focusing largely on roles that the state could play in the climate-related adaptation or mitigation efforts of certain sectors of Pennsylvania's population, environment and economy. Where significant barriers to these economic or policy opportunities exist, we have identified the nature of these barriers and have suggested policy steps that might help overcome these barriers.

We have classified identified opportunities into two categories; a summary of the opportunities in each category is given in Table 14.1.

Opportunities driven by climate-related policy: There are a number of economic opportunities for Pennsylvania that are related to climate change but are unlikely to arise without appropriate policy measures in place. Opportunities that likely require some amount of forcing from public policy include the development of carbon sequestration resources and opportunities related to energy production and consumption. Many policy-drive opportunities would be aimed at mitigating greenhouse gas emissions, both immediately and in the future. Some opportunities related to energy consumption behaviors in Pennsylvania will also contribute to adaptation to future climate change. Virtually all of the policy-driven opportunities can be taken advantage of immediately, or in the very near future (within perhaps five to 10 years).

Opportunities driven by the impacts of climate change: A second set of opportunities will arise in response to future climate realizations. These opportunities primarily involve adapting to a warmer climate in Pennsylvania, and as such will not be available until future warming is actually realized. Explicit public policies may not be required for the Commonwealth to take advantage of these opportunities, but some amount of public education or public-private partnership may be required.

The opportunities identified in this report are not all mutually exclusive. Significant synergies may exist between opportunities or between sectors. Clear examples of cross-sector synergies might include:

- Terrestrial sequestration in Pennsylvania's agricultural lands and changes in agricultural practices through conservation tilling;
- Renewable energy development and a transition to electrified transportation;
- Maintaining ecosystem and freshwater services and increased opportunities for warm-weather outdoor recreation in Pennsylvania.

In addition, the aggressive development of some opportunities may hamper the development of other opportunities. Some opportunities may simply disappear, or may become less beneficial. Examples might include:

- Reducing overall energy consumption through efficiency measures or self-generation lowers the cost of energy commodities for all consumers in

Pennsylvania. This diminishes some of the incentives for managing peak demand, particularly for electric power.

- If aggressive climate policy is successful in mitigating some amount of expected future warming, some opportunities driven by climate change, such as increased warm-weather recreation, will be significantly diminished.
- If significant amount of cropland is converted to forest land in response to certain terrestrial sequestration opportunities, the ability of Pennsylvania's agricultural sector to benefit economically from new warmer-weather agricultural products will be diminished.
- Geologic pore space in Pennsylvania may face conflicting uses, such as CO_2 sequestration and the development of unconventional natural gas sources.

Opportunities Driven by Climate Policy	Opportunities Driven by Climate Change
1. A CO_2 Sequestration Services Sector:	*1. New Risk-Management Products:*
- Geologic	- Agricultural
- Terrestrial (Agricultural)	- Consumer, Commercial and Residential
- Forests	*2. Warm-Weather Outdoor Recreation*
2. Managing Peak Electricity Demand	*3. New Agricultural Products*
3. Reducing Overall Energy Consumption:	*4. New Forestry Products and Practices*
- Energy Efficiency	*5. Maintaining Ecosystem Services and Freshwater Services*
- Self-generation and Co-generation	
4. Renewable Energy Development	
5. Alternative Transportation Fuels:	
- Electrified Transportation	
- Low-Carbon Biofuels	
6. Agricultural GHG Mitigation	

Table 14.1. Economic opportunities related to climate change in Pennsylvania.

As emphasized in Section 10, many climate-related economic opportunities available to Pennsylvania, particularly in the energy sector, will continue to be hampered by regulatory uncertainty related to state or federal approaches to climate policy. Some economic opportunities would require significant investments in capital or infrastructure. In order to ensure that industry and service sectors such as electrified transportation and carbon sequestration will emerge and thrive, the Commonwealth needs to develop a comprehensive climate policy. Delaying such a policy simply serves to increase uncertainty.

Quantifying the potential size or scope of any single climate-related economic opportunity (or set of opportunities) would be an inherently subjective task, given the

current state of knowledge regarding climate futures for different regions of Pennsylvania, and the lack of sector-specific data and modeling. An additional complication is that the scope of many of the opportunities will likely be determined by future and still-uncertain climate policy at the state, regional and federal level. The focus of this report is on identifying potential opportunities, rather than attempting to estimate the amount of economic activity that might be associated with each opportunity, or the degree to which economic activity is the result of shifts in Pennsylvania's economy, rather than entirely new economic activity.

14.1 Economic Opportunities Driven by Climate Policy

The public policy response to climate change in Pennsylvania has the potential to create a number of economic opportunities for new businesses or industries to emerge in the Commonwealth. Some of these policy-driven economic opportunities will not themselves result in the creation of wholly new jobs or industries, but may provide economic outlets for individuals or sectors economically harmed by climate change in Pennsylvania.

14.1.1 A Pennsylvania Carbon Transportation, Sequestration and Services Sector

Geologic Sequestration

The capture and geologic sequestration of CO_2 from large point sources (primarily power plants) represents a significant opportunity for an entirely new industrial sector to emerge in Pennsylvania. This industry would contribute to climate-change mitigation in the Commonwealth, and could potentially allow for the Commonwealth to sell mitigation services (in the form of geologic long-term storage of carbon dioxide) to surrounding states. Pennsylvania is considered to have the highest geologic sequestration potential of all major Midwestern coal-producing states. Initial estimates from the Midwest Regional Carbon Sequestration Partnership suggest that Pennsylvania could easily sequester hundreds of year's worth of CO_2 emissions from large stationary sources. The Pennsylvania DCNR is currently in the process of updating these estimates, per its sequestration assessment mandated under Act 129. The potential for offering sequestration services to Pennsylvania carbon emitters, or to emitters from other states is thus quite high. The potential for supplying sequestration services to other states increases as the costs of carbon emissions increase (through federal or state policy actions such as the Northeastern Regional Greenhouse Gas Initiative, for example).

A number of legal, regulatory and social barriers need to be addressed before a Pennsylvanian geologic carbon sequestration industry could emerge. Issues surrounding property rights for pore space, siting of CO_2 transportation infrastructure, liability and public acceptance need to be carefully thought through. The current regulatory structures governing pore space and mineral rights, both at the state and federal level, amount to an endorsement of a "first-mover" policy. It is far from clear that such a policy is in the best long-term economic interest of the Commonwealth.

Some of the highest-potential sequestration sites in Pennsylvania adjoin areas currently being developed for Marcellus Shale production. For example, the Oriskany formation, which is separated from the Marcellus formation by a relatively thin layer of rock, is considered to hold promise for geological carbon sequestration. Although some uncertainty remains, it is just as likely as not that sequestration and natural gas development (or gas storage, in some areas) represent competing uses for adjoining shale formations. The Commonwealth may face tradeoffs between these competing uses. At the very least, for example, it appears that some risk of releasing CO_2 during hydrofracturing might exist if sequestration and unconventional gas development take place in the same area. Further investigation and perhaps an explicit cost-benefit study should be undertaken regarding whether conflicts exist between the use of the Marcellus Shale and adjoining formations for natural gas production, storage or carbon sequestration, and what the highest-value use of these geologic formations would be.

Terrestrial Sequestration in Agricultural and Forest Land

Pennsylvania farmland also has the potential for terrestrial sequestration of atmospheric carbon. Options for terrestrial sequestration in the agricultural sector would include conversion of cropland to pasture or forest, planting of winter cover crops, reduced tillage practices, organic farming, and planting trees or biofuel crops on marginal agricultural land. Pennsylvania farmers are likely to be sensitive to carbon prices in choosing to alter land-management practices for terrestrial carbon sequestration. At a price of $10 per metric ton of permanently sequestered carbon, farmers would mainly adopt conservation tillage as their mitigation strategy. At prices of $25 or higher, significant amounts of cropland might be converted to forest.

Additional terrestrial sequestration opportunities exist in Pennsylvania's forests, as discussed in Section 7. While it may be difficult to substantially increase the growth rates of Pennsylvania hardwoods, additional carbon can be sequestered and stored in the state's forests by increasing stocking levels or reducing stocking reductions. Policies aimed at terrestrial carbon sequestration in forests should focus on preventing forest loss, rather than attempting to increase the number of forested acres. Since 70 percent of Pennsylvania's forests are privately owned, often in small, family-owned parcels, it will be necessary to engage private forest landowners if significant changes are to be made in how Pennsylvania's forests are managed.

14.1.2 Services for Managing Peak Electricity Demand

Since some amount of future warming is virtually certain in Pennsylvania (see Section 4.4.2), in the absence of significant changes in consumer behaviors or energy use, climate change is virtually certain to result in an increased demand for cooling in the summer and a decline in the demand for heating in the winter. Since virtually all cooling in the Commonwealth uses electricity, but only 17 percent of Pennsylvania households have electric heat, climate change will likely increase the annual demand for electricity. Peak demand for electricity will likely grow faster than average demand. Some uncertainty exists surrounding the impact that climate change will have on the annual energy bill (electricity plus heating fuels) for a given household or commercial business. Much more

certain are the costs to consumers and to the PJM electricity system of peak electricity demand increases of up to 9 percent (see Section 10). Not only will peak demand management involve the construction of expensive generation infrastructure, additional grid-hardening investments would likely be necessary to maintain reliability. These investments will increase costs to consumers.

Reducing peak electricity demand through load-shifting (increasing some electricity use at night and decreasing some use during the day) would reduce the financial costs of climate change by reducing needed investments in peaking generation and supporting infrastructure. Currently, PJM offers a number of different programs through which consumers can bid load reduction into the markets and receive payments for doing so. Efforts by the Commonwealth to encourage reduction in peak demand (through, for example, time-differentiated electricity pricing) would provide additional opportunities for the load aggregators that facilitate participation in demand reduction programs. The peak demand reductions mandated by Act 129 are a good start, but the Commonwealth will require a longer-term plan for managing peak electric demand, and identifying the most cost-effective demand reduction opportunities.

14.1.3 Opportunities to Provide Increased Energy Efficiency

Decreasing Overall Energy Use

Climate change will not be the only factor increasing future electricity demand in Pennsylvania. Population growth and changes in economic activity will increase overall electricity demand. Reducing peak demand for electric power (Section 10 and 14.1.3) is not the only economic opportunity related to the energy sector and the mitigation of climate-change impacts. Increased energy efficiency, which involves using less energy while maintaining a high standard of living, represents a significant economic opportunity if appropriately encouraged by the Commonwealth. Home weatherization and the adoption of energy-efficient space conditioning technologies could contribute to both mitigation of future climate impacts and adaptation to current climate change. Air conditioning from ground-source or air-source heat pumps, for example, could provide an equivalent level of comfort as window-unit air conditioners while using a fraction of the energy input (Section 10).

Energy-efficiency space-conditioning technologies could also contribute to mitigating some human health impacts from climate change, such as reducing deaths related to extreme heat. Comfortable indoor climates may also mitigate health effects from illnesses associated with hot days.

Opportunities to Support Self-Generation and Co-Generation

Additional emissions reduction opportunities in the electric power sector exist through increased use of co-generation and self-generation (or “distributed generation”) technologies. Pennsylvania companies already generate more than 1,000 MW of their own electricity, and have reported significant cost savings, particularly through the use of combined heat and power (CHP), where waste heat from the power generation process is used in industrial processes or to heat water. As discussed in Section 9, the use of

anaerobic digesters to produce methane from livestock wastes could also reduce the demand for utility-supplied electric power. The use of digesters would not entirely eliminate waste-management needs in Pennsylvania's agricultural sector, but would contribute to meeting the waste-management challenge. Other opportunities may be available to reduce emissions and lower costs through co-generation or self-generation "micro-grids," particularly in malls, campuses or office parks that demand both electricity and heat. A number of distributed energy technologies (particularly digesters and renewables) have costs that are higher than buying power from the utility. Placing a price on carbon dioxide emissions from power generation through a tax or cap-and-trade system, along with policies to reduce the costs of distributed energy systems, may increase their adoption and use within Pennsylvania.

14.1.4. Opportunities for Low-Carbon Electricity Production

Low-carbon sources of electric power generation will be a necessary component of any strategy to mitigate greenhouse gas emissions. The use of fossil fuels could be consistent with a low-carbon energy strategy, if the right policies and institutions are in place to support investments in carbon capture, transportation and storage technologies, as well as advanced fossil generation technology which likely lowers the cost of CO_2 capture. Renewable electricity generation technologies are commercially available and are experiencing significant growth in the U.S., but developing the best of these resources will require significant investments in transmission infrastructure. Since these generation sources are inherently intermittent, the portfolio of resources used to provide maintain electric reliability when the wind is not blowing or the sun is not shining will determine whether these generation sources have low emissions throughout the life-cycle. Pennsylvania's Alternative Energy Portfolio Standard (AEPS) has already provided incentives for renewable energy development, particularly for wind power. The AEPS also contains a set-aside for solar photovoltaic power. The Commonwealth may wish to investigate whether encouraging additional renewable energy development may be cost-effective.

14.1.5 Transitioning to Electrified Transportation and Alternative Fuels

The demand for transportation fuels is driven primarily by population growth and economic growth. Climate change *per se* is not expected to have a significant effect on the demand for transportation fuels. There may, however, be a number of synergies between transitioning away from petroleum-based transportation fuels and other efforts to mitigate or adapt to climate change. Plug-in hybrid electric vehicles (PHEVs) offer an attractive pathway to addressing problems in the integration of large-scale renewable power generation, meeting peak electricity demand and in transitioning away from petroleum fuels for energy security reasons. As discussed in Sections 7 and 9, biomass fuel sources (from energy crops grown by Pennsylvania farmers or from forested areas) could be used in conjunction with electrified transportation to significantly reduce the use of gasoline or diesel fuel. Taking advantage of these opportunities will require a significant commitment to the de-carbonization of the electric power sector, and the

development of policies and pilot projects to promote the growth of "smart grid" communications and control technologies.

14.1.6 Greenhouse gas Reduction from Pennsylvania Agriculture

A number of opportunities exist for reduction in greenhouse gas intensity from the agricultural sector, as discussed in Section 9. Changes in agricultural practices that could reduce greenhouse gas emissions include reduced fossil fuel use, changes in manure storage and handling practices, improving crop residue management, and use of low-emission fertilizers. One option that could reduce greenhouse gas emissions and provide a source of energy is constructing manure digester and methane recovery facilities at concentrated animal feeding operations (CAFOs). Following recovery, the methane is cleaned of impurities and converted to electricity via an engine-generator set, which can be used on the farm or added back to the grid. These technologies are likely to become more cost-effective if a price is placed on carbon dioxide or other greenhouse gas emissions through a tax or cap-and-trade system.

14.2 Economic Opportunities Driven by the Impacts of Climate Change

14.2.1 Opportunities for Risk-Management Services

As discussed in Sections 9 and 13, climate change is likely to increase the demand by farmers and energy consumers for risk management products. Agricultural producers currently have a range of risk management products from which to choose, including yield insurance against losses due natural causes such as drought, excessive moisture, hail, wind, frost, insects, and disease; catastrophic loss insurance; gross revenue insurance that protects against gross revenue falling below a specified level; and adjusted gross revenue insurance that insures the revenue of an entire farm rather than a specific crop. Weather derivatives for energy consumers and agricultural producers provide another opportunity for the insurance industry.

The insurance industry could also offer products to individual consumers or homeowners that encourage mitigation or adaptation to future climate change in Pennsylvania. Pay-as-you-drive insurance could reduce the demand for transportation fuels. Adaptation-related opportunities exist in providing incentives to reduce climate-related risks. Examples would include avoiding building residences and commercial buildings in area that will be more prone to floods or wildfires, and the use of weather-resistant materials in new construction and in retrofitting older buildings. Unlike in other states with a larger risk exposure to climate change, the reinsurance market is unlikely to grow significantly in Pennsylvania.

As discussed in Section 10, climate change in Pennsylvania has the potential to reduce electric reliability. In a warmer climate, trees may grow faster or in such a way that keeping up with tree-trimming becomes difficult and costly for electric utilities. Increased flooding may affect some substations on the transmission or distribution grid. The risk of blackouts on the distribution system increases with demand; if peak electricity

demand grows as a result of a warmer future climate in Pennsylvania, the risk of interruptions in electric service is likely to increase accordingly. The costs of interruptions in electric service are very high for some businesses. If the risks associated with electric reliability can be properly priced, the insurance industry in Pennsylvania could market a reliability-risk-management product to qualified business or commercial customers.

14.2.2 Warm-weather Outdoor Recreation Services

Climate change in Pennsylvania will have negative impacts for winter-based outdoor recreation (skiing, snowmobiling and trout fishing, for example), while other recreation sources will benefit significantly from warmer weather (swimming and boating, golf, and warm-water fishing, for example). While there are few mitigation opportunities for winter recreation opportunities that rely on natural snow, the effects of climate change could be mitigated somewhat by the increased use of artificial snowmaking. Winter sports resorts should be encouraged to replace or upgrade old snowmaking systems with newer, more energy-efficient systems, where such upgrades would make economic sense.

Similarly, warmer summer temperatures and a longer summer season will increase demand for water-based recreation and forms of outdoor exercise. The Commonwealth could capitalize on this increased demand by ensuring the health of Pennsylvania's water resources (see Section 6) or providing more opportunities for water-based recreation (see Section 12). For example, the Commonwealth could develop new access points for stream and river-based recreation. Or, the Commonwealth could consider constructing new reservoirs. Additional public lands dedicated to recreational use, such as for hunting, camping or hiking could support both the increased demand for these outdoor activities and the industries and businesses that support these activities. The Commonwealth could also assist communities in planning for increased demand for forms of outdoor exercise such as bicycling, jogging and some team sports. These investments could also reduce the public health costs associated with climate change, and in some communities could provide alternatives to private automobiles for transportation.

14.2.3. Opportunities for Agricultural Adaptation to Climate Change

The ability of Pennsylvania agriculture to adapt to climate change hinges in part on the development and adoption of new crop varieties and livestock breeds suited to a warmer and more variable climate. The existence of a productive and dynamic agriculture in states to the south of Pennsylvania demonstrates that Pennsylvania agriculture can continue to prosper in a warmer climate, but changes will be required. Any producers who fail to adjust to climate change are likely to see their yields and profitability decline.

Climate change will require changes in the types of crops that are grown in Pennsylvania. The future of agriculture in Pennsylvania may to some extent resemble the mix of crops currently grown in states to the south of Pennsylvania. The agricultural opportunities in Pennsylvania primarily revolve around shifting away from crops that are suited to colder weather, such as alfalfa, apples and potatoes, and towards warmer-weather substitutes

such as tomatoes, sweet corn and southern hay varieties. Pennsylvania grape-growers and wineries may choose to replace some of their native American grape varieties with European varieties that do better in a warmer climate.

A shift towards more organic and locally-produced agriculture represents both an opportunity and a challenge for Pennsylvania farmers to adapt to a warmer climate where rainfall is more variable and the frequency of intense precipitation events increases. The demand for locally-produced agricultural products may partially limit the shift by Pennsylvania farmers to warm-weather crops; these farmers will likely see their yields decline in a warmer Pennsylvania climate. Organic practices that maintain or increase organic matter in soils may cause soils to retain significantly more rainwater, which may help farmers weather dry periods that may occur with climate change. On the other hand, changes in weed and insect pest types and pest populations created by climate change might create challenges for organic producers. Shifts in consumer preferences towards locally-grown organic foods could assist or limit Pennsylvania farmers in adapting to climate change.

Although Pennsylvania farmers do not need to take significant adaptive measures immediately, research and development into new crop varieties suited to Pennsylvania's future climate needs to begin soon, since the time lag between research and commercialization can easily reach 20 or 30 years (Alston, Craig and Pardey 1998). These additional resources might potentially come at the expense of resources devoted to advancing agricultural technology in other ways.

14.2.4. Opportunities for New Forestry Products and Practices

Climate change is likely to make Pennsylvania a more hospitable environment for warmer-weather tree species such as oaks and hickories, and less suitable for northern hardwood species such as birches, maples and cherries. These species will likely see their numbers dwindle, and under some extreme climate scenarios could be eliminated from Pennsylvania altogether. Thus, forest managers and landowners in Pennsylvania will likely need to shift away from the historical practice of producing high-value hardwoods and veneers. Adaptation of forests is likely to be more difficult than in some other sectors, since forest ecosystems in unstable climates may experience increased mortality rates.

Some synergies exist between the opportunities for terrestrial CO_2 sequestration in Pennsylvania's forests and opportunities for forestry practices in the face of climate change. Section 8 suggests that preventing forest loss represents the greatest opportunity to maintain healthy forests in the face of climate change. Many changes in forest management practices by public or private stakeholders will need to anticipate the future impacts of climate change, rather than simply reacting to climate change. Forest managers may begin planting more southern seeds, for example. It is possible to alter forest management practices to promote faster-growing trees, either for carbon sequestration purposes or as one way of adapting forests to climate change. Such a

strategy generally requires a shift away from natural forests towards highly managed plantation forests.

Increased demand for woody biomass could offer opportunities for forest managers and landowners. Woody biomass, used for energy production, for example, provide a market for low value species and trees that today often cost more to harvest than what they are worth. Having a market for this so-called "low-use" wood makes a larger variety of silvicultural management options financially viable.

As with agriculture, research is needed now to improve our forecasts of Pennsylvania's climate future, and to identify tree species that are most likely to thrive in different regions of Pennsylvania. Efforts at forest recomposition in Pennsylvania will need to begin decades before significant climate change occurs. Additional research is needed to improve the monitoring of forest health in Pennsylvania as the Commonwealth's climate changes.

14.2.5. Maintaining the Value of Pennsylvania's Ecosystem and Freshwater Services

Pennsylvania's natural resources and systems provide a number of valuable services to the population and the economy. In some cases, climate change may constrain the ability of natural resources to provide these services. As part of any comprehensive climate policy, the Commonwealth should include as an explicit goal the maintenance of ecosystem services, where cost-effective and appropriate.

Section 6 discusses the services provided by Pennsylvania's watersheds, including supplying municipal drinking water, irrigation, flood management, and contributing to the production of electric power. Under some climate scenarios, extended dry periods or droughts may become more common, necessitating adaptation strategies for maintaining water-related services during dry spells. Section 6 lays out strategies for water-recycling measures and other demand- and supply-side adjustments that could increase reliability of water supply in a future with drier summers and wetter winters.

It should be emphasized here that uncertainty exists surrounding how climate change will impact Pennsylvania's watersheds, since to date there has not been sufficient monitoring of hydrological variables to provide a historical benchmark, and little effort has been made on statewide modeling studies to interpret past observations and future projections of climate. The temporal dynamics of Pennsylvania's waterways are thus poorly understood. This uncertainty is particularly important for Pennsylvania since a large number of the Commonwealth's major river systems originate in a large number of small headwater streams.

Related to the services provided by water supplies are those services provided to and by aquatic ecosystems. As discussed in Sections 8 and 12, climate change may limit the ability of Pennsylvania river systems to support valuable coldwater species due to the likely warmer of its water bodies, which among other services support an important fishing industry in the Commonwealth. Reduction in scale and reach of wetlands also

inhibits natural flood control in some areas of the Commonwealth. Strategies and policies to avoid these and other potential impacts from climate change (discussed in Section 8) need to center around maintaining and improving the resiliency of aquatic systems through minimization of nutrient enrichment, hydrologic modification, habitat fragmentation and degradation, and species loss.

Appendix 1: IPCC Emissions Scenarios

The IPCC scenarios are intended to address uncertainty over demographic development, socio-economic development, and technological change. Scenarios are based on one of four storylines with all scenarios within each storyline part of that storyline "family." The scenario families are A1, A2, B1, and B2. There are three scenario groups within A1 and one in each of the others, creating a total of six scenario groups.

A1 Storyline

The A1 scenario is characterized by high rates of economic growth. Population growth increases until mid-century and declines afterwards. The scenario also assumes a rapid introduction of new and more efficient technologies. This results in and enables relatively energy intensive lifestyles. The major themes characterizing the A1 scenario include: convergence among regions, capacity building, increased cultural and social interactions, and reduced regional differences in per capita income. Economic convergence is facilitated by technological development, increased international cooperation and national regulatory changes.

The A1 storyline is divided into three scenario groups (A1F1, A1B and A1T) with each assuming an alternative energy technology mix. The A1F1 group assumes a fossil fuel intensive energy mix. A1B assumes a balanced energy mix and thus does not rely too heavily on any one energy source. It is assumed that technological changes apply evenly to all energy types and supply sources. Finally, A1T assumes a primarily non-fossil fuel energy mix.

A2 Storyline

The A2 storyline assumes a very heterogeneous world. As a result, it is characterized by themes of self-reliance and preservation of local identities. Population growth rates are continuously increasing because of slow convergence of fertility patterns across regions, creating the largest population of all of the storylines. Economic development is primarily at the regional level. This results in varied rates of economic growth across regions. As a result, the world is characterized by significant income inequality, particularly between the developed and developing world. Technological development follows a similar pattern and new technologies are diffused slowly. Both economic growth and technological change are slower than in the other storylines. The heterogeneous nature of the A2 storyline also presents itself in more varied governments across regions. Environmental concerns are locally based, with little global cooperation in environmental policy. Regional resource availability determines the energy mix utilized within regions.

B1 Storyline

A convergent world characterizes the B1 storyline. Worldwide, the population grows through mid-century and declines afterwards. Major themes are increased levels of global integration and more concern for economic, social, and environmental sustainability. As a result, development becomes more socially and environmental

conscious. The structure of the economic system transitions quickly to a service and information oriented economy, with a resulting decrease in the consumption of material goods. There are efforts to decrease income inequality. However, these socially and environmentally conscious efforts may compromise economic efficiency and distort markets. Rapid technological innovation combined with an effective global institutional structure to diffuse these technologies results in expanded use of cleaner and more energy efficient technologies. These factors contribute to a high level of environmental quality in the B1 storyline. Oil and gas use decline as the world makes a relatively smooth transition to alternative energy use.

B2 Storyline

The B2 storyline is characterized by an emphasis on local solutions to economic, social, and environmental sustainability. The global population increases continuously, but at a rate lower than in the A2 storyline. As a result of a local emphasis, international institutions become less important. There are intermediate levels of economic development. Incomes converge at the local level. Though there is some convergence in incomes worldwide, an emphasis on local solutions results in a slower convergence than in storylines characterized by high levels of global integration. Technological change is less rapid and less diffused globally but more regionally diverse than in the B1 and A2 storylines. Environmental policy is focused at the local and regional level, with global environmental initiatives less important. Energy use is heterogeneous, with resource endowments influencing the regional energy mix. Globally, energy use transitions towards alternative energies, but this transition is gradual and the global energy system relies primarily on fossil fuel energy sources.

Economic emphasis

Global integration

A1 storyline World: market-oriented Economy: fastest per capita growth Population: 2050 peak, then decline Governance: strong regional interactions; income convergence Technology: three scenario groups: • **A1FI**: fossil-intensive • **A1T**: non-fossil energy sources • **A1B**: balanced across all sources	**A2 storyline** World: differentiated Economy: regionally oriented; lowest per capita growth Population: continuously increasing Governance: self-reliance with preservation of local identities Technology: slowest and most fragmented development
B1 storyline World: convergent Economy: service and information-based; lower growth than A1 Population: same as A1 Governance: global solutions to economic, social and environmental sustainability Technology: clean and resource-efficient	**B2 storyline** World: local solutions Economy: intermediate growth Population: continuously increasing at lower rate than A2 Governance: local and regional solutions to environmental protection and social equity Technology: more rapid than A2; less rapid, more diverse than A1/B1

Regional emphasis

Environmental emphasis

Figure A.1.1 Source: Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Appendix 2: Soil Moisture Model

The soil moisture model used in the water resources section is based on research by Porporato et al. (2004), Laio et al. (2001) and Rodriguez-Iturbe et al. (1999). The evapotranspiration equation is taken from Shuttleworth (1993). The model is discussed in detail in those papers, but the main input variables and equations are listed below.

<u>Assumptions</u>

The following assumptions are made in the derivation of the model:

- Soil moisture analyzed at a daily timescale;
- Vertical and horizontal spatial variability in the soil are neglected;
- Lateral water flow is neglected (no topography);
- Soil is treated as a reservoir that is filled by precipitation and emptied through evaporation and losses to deep groundwater and surface runoff;
- The storage capacity of the soil 'reservoir' is the active depth of the soil, defined as the rooting depth of the vegetation multiplied by the porosity of the soil;
- Soil moisture is vertically averaged over the vegetation rooting depth;
- Porosity and rooting depth are time invariant parameters;
- When soil moisture exceeds a value of s^1 ($s_{fc}<s^1<1$), water is immediately lost to surface runoff and deep groundwater;
- Evapotranspiration stops at the wilting point of the vegetation, defined as when the relative soil moisture reaches a value of $s=s_w$ and;
- Evapotranspiration decreases linearly from a maximum value (PET, estimated by the Hargreaves equation) at $s=s^1$ to 0 at $s=s_w$.

Table A.2.1 Soil Moisture Model Equations

Soil Water Balance

$$nZ_r \frac{ds}{dt} = R(t) - ET(s(t)) - L(s(t)), \qquad 0 \leq s \leq s_1 \tag{1}$$

$$R = \alpha\lambda \tag{2}$$

$$PET = .0028S_o\sqrt{\delta_T} * (T + 17.8) \tag{3}$$

Dimensionless Numbers

$$\frac{\lambda}{\eta} = \frac{\lambda w_a}{PET} \tag{4}$$

$$D_I = \frac{\gamma\eta}{\lambda} = \frac{PET}{R} \tag{5}$$

$$\gamma = \frac{w_a}{\alpha} \tag{6}$$

$$\eta = \frac{PET}{w_a} \tag{7}$$

$$w_a = (s_1 - s_w) * nZ_r \quad \text{(not dimensionless)} \tag{8}$$

Effective Soil Moisture

$$x = \frac{(s - s_w)}{(s_1 - s_w)} \tag{9}$$

$$\langle x \rangle = \frac{1}{\eta\gamma(\lambda - Ne^{-\gamma})} \tag{10}$$

Effective Soil Moisture PDF

$$P(x) = \frac{N}{\eta} * x^{\left(\frac{\lambda}{\eta}\right)-1} * e^{-\gamma x} \tag{11}$$

$$N = \frac{\eta\gamma^{\frac{\lambda}{\eta}}}{\Gamma\left(\frac{\lambda}{\eta}\right) - \Gamma\left(\frac{\lambda}{\eta}, \gamma\right)} \tag{12}$$

Table A.2.2 Input Variables Soil Moisture Model

Variable Name	Variable Description	Units	Scale
Mean rainfall depth	Average rainfall amount per rainfall event*	mm	daily
Frequency of rainfall	Number of rainfall events per day*	day^{-1}	Calculated using daily rainfall data
Temperature	Average daily temperature	^{o}C	daily
Temperature Range	Difference between the daily high and low temperatures	^{o}C	daily
Porosity	Porosity of the soil	-	time invariant
Field Capacity	Value of relative soil moisture where losses to groundwater begin	-	time invariant
Wilting point	Value of relative soil moisture where plant transpiration stops	-	time invariant
Rooting depth	Depth of roots in vegetation	mm	time invariant

*- Each day that it rains is assumed to be a separate rainfall event, therefore, frequency is calculated by number of days with precipitation / number of days without precipitation (Laio et al., 2001)

Table A.2.3 Soil Moisture Model Parameters

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n (dimensionless) is the vertically averaged soil porosity,

Z_r (mm) is the vegetation rooting depth, s (dimensionless) is relative soil moisture,

R (mm) is the rainfall,

ET (mm) is evapotranspiration,

L (mm) is losses to groundwater and surface runoff,

w_o (mm) is the maximum soil water storage available to vegetation,

s_1 (dimensionless) is the relative soil moisture threshold, s_w (dimensionless) is the wilting point of the vegetation,

γ (dimensionless) is the ratio between maximum soil water content and average rainfall event depth,

α is the average rainfall event depth, η (dimensionless) is the normalized evapotranspiration loss under well-watered conditions,

λ (day^{-1}) is the frequency of rainfall events, PET (mm/day) is the potential evaporation, D_I (dimensionless) is Budyko's dryness index,

S_o (mm/day) is the water equivalent of extraterrestrial radiation,

δ_T (degrees C) is the difference between the mean monthly minimum and mean monthly maximum temperatures,

T (degrees C) is the temperature, x (dimensionless) is the effective relative soil moisture, $\langle x \rangle$ (dimensionless) is the analytical solution for mean effective relative soil moisture,

N (dimensionless) is the normalization constant for the truncated gamma distribution,

P(x) (dimensionless) is the probability function for x,

$\Gamma(.)$ is the gamma function

$\Gamma(.,.)$ is the incomplete gamma function.

Appendix 3: Locations of Stream Temperature Measurements

River	Water Temperature Location	Air Temperature Location	Period of Record	A (mi^2)	Q (ft^3/s)	Δt	Y-Intercept A	Slope B	NSE	N
Big Spring Creek	Big Spring, PA	State College, PA	2005-2007	3.41	27.8	D	11.11	.02	.13	1092
						W	11.11	.02	.12	156
						M	11.10	.02	.12	36
Manada Creek	Manada Gap, PA	Harrisburg, PA	2005-2007	8.59	17	D	3.11	.65	.93	1010
						W	2.87	.67	.96	153
						M	2.70	.68	.98	36
Juniata River	Huntingdon, PA	Harrisburg, PA	1997-2003	960	1110	D	5.68	.80	.17	2482
						W	4.92	.88	.55	362
						M	4.37	.93	.77	84
Lehigh River	Easton, PA	Allentown, PA	2002-2006	1364	2850	D	5.99	.70	.93	891
						W	3.57	.83	.96	140
						M	5.61	.74	.98	38
Delaware River	Point Pleasant, PA	Allentown, PA	2002-2006	6570	10800	D	6.65	.77	.88	705
						W	3.83	.91	.95	121
						M	4.18	.91	.97	33
Delaware River	Philadelphia, PA	Philadelphia, PA	2002-2007	7993	11800	D	1.19	.86	.88	2053
						W	0.99	.92	.95	306
						M	0.56	.95	.97	72

A: Drainage Area, Q: Mean Annual Discharge, Δt: Time Step of Data, D: Daily, W: Weekly, M: Monthly, NSE: Nash-Sutcliffe Efficiency Measure, N: Number of Data Points

Appendix 4: The PHIM Model

Feature/ Time Series	Property	Source
Soil	Porosity; Sand, Silt, clay Fractions; Bulk Density	CONOUS, SSURGO and STATSGO http://www.soilinfo.psu.edu/index.cgi?soil_data&conus http://datagateway.nrcs.usda.gov/NextPage.asp http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/
Geology	Bed Rock Depth; Horizontal and Vertical Hydraulic Conductivity	http://www.dcnr.state.pa.us/topogeo/ , http://www.lias.psu.edu/ems1/guides/X.thml
Land Cover	LAI	http://glcfumiacs.umd.edu/data/landcover/data.shtml , http://ldas.gsfc.nasa.gov//LDAS8th/MAPPED.VEG/LDASmapveg.shtml
	Manning's Roughness	Hernandez et.al, 2000
River	Topology: From Node – to Node, Neighboring Elements;	Derived using pihmGIS (Bhatt et.al., 2007)
	Manning's Roughness	Dingman (2002)
	Coefficient of Discharge	ModHms Manual
	Shape and Dimensions;	Derived from regression using depth, width and discharge data from http://nwis.waterdata.usgs.gov/usa/nwis/measurements
Forcing	Precipitation Temperature	Gauge data obtained from MARFC. 6 hourly precipitation point data is spatially gridded such that it conforms to the monthly precipitation distribution map obtained from parameter-elevation regressions on independent slopes model (PRISM) (Daly et. al., 1994,1997)
DEM		**http://seamless.usgs.gov/**
Streamflow		**http://nwis.waterdata.usgs.gov/nwis/sw**

PIHM is a multi-process, multi-scale hydrologic model where the major hydrological processes are fully coupled using the semi-discrete finite volume method. The model itself is "tightly-coupled" with PIHMgis, an open-source Geographical Information System designed for PIHM. The PIHMgis provides the interface to PIHM, access to the digital data sets (terrain, forcing and parameters) and tools necessary to drive the model, as well as a collection of GIS-based pre- and post-processing tools. Physically-based fully-distributed hydrologic models try to simulate hydrologic state variables in space and time while using information regarding heterogeneity in climate, land use, topography

and hydrogeology. However incorporating a large number of physical data layers in the hydrologic model requires intensive data development and topology definitions. Traditionally GIS has been used for data management, data analysis and visualization. But proprietary data structures, platform dependence, isolated data model and non-dynamic data-interaction with pluggable software components of existing GIS frameworks, makes it restrictive to perform sophisticated numerical modeling. Therefore, PIHM was developed with this "tightly-coupled" GIS interface that is open source, platform independent and extensible. The tight coupling between GIS and the model is achieved by developing a shared data-model and hydrologic-model data structure.

Appendix 5: IFSM Results for Agriculture in the Absence of Adaptation

As the agriculture section of this report indicates, the existence of a productive and dynamic agriculture in states to the south of Pennsylvania demonstrates that Pennsylvania agriculture can continue to prosper in a warmer climate, but changes will be required. Producers who fail to adjust are likely to see their yields and profitability decline. This appendix contains estimates derived from the Integrated Farm System Model (IFSM) that illustrate what could happen to yields and profitability in the absence of adaptation by producers to climate change.

IFSM is a simulation tool that integrates the many biological and physical processes on crop, beef, and dairy farms (Rotz et al. 2008). The model excels at integrating and linking the major components of agricultural production in a manner that adequately represents the most important interactions among the many biological and physical processes on the farm. The model holds constant a number of variables that farmers are likely to adjust in a warmer climate: crop varieties; crop acreages; livestock breeds; numbers of animals at various ages; harvest, tillage, and manure handling strategies; equipment and structures; and planting and harvesting dates.

Simulation results were used to predict production costs, income, and farm net return or profit for each year of 20 years of weather (Rotz et al. 2008). Four farm operations were simulated under current weather conditions and those predicted by the Parallel Climate Model developed by Oak Ridge National Laboratory.[15] The four operations are a large dairy (1,000 cows), a corn-soybean farm (1,000 acres), a cow-calf operation (140 cows), and a small organic dairy (50 cows).

For all four operations, IFSM predicts losses in net returns to management. The large dairy sees milk yields fall by 1,200 pounds per cow, translating into a loss of $237 per cow in annual revenue. The loss of milk production and the corresponding fall in returns can largely be explained by heat stress on the animals and reduced feed quality and corn grain yields. Increased soil moisture results in higher neutral detergent fiber (NDF) levels in alfalfa forage, lowering overall quality. Poorer quality forage leads to increased supplementation of grain and concentrates and lower production from reduced feed intakes in animals fed higher fiber diets.

For the organic dairy, IFSM finds that milk production is not affected by climate change. The lower level of milk yield on this farm could be maintained in a warmer climate. However, net returns to management fall by $162 per cow due to reduced sales of excess feed produced on the farm. Feed sales decline with corn grain, soybean and wheat yields. The corn-soybean operation sees yields fall by approximately 18 and 3 bushels per acre respectively. This translates into a loss in annual profit of $32,713. The cow-calf

[15] Data were generously provided by Katharine Hayhoe of the Department of Geosciences at Texas Tech University.

operation sees annual returns fall by $7,705, almost solely due to its reliance on grazing. Grass yields fall by 0.4 tons per acre.

These results are not a prediction of what will happen to Pennsylvania agriculture, but what could happen to producers who fail to adjust their operations in response to climate change. Producers who wish to maintain or increase their profitability should look to adjustments in the variables held constant here: crop varieties; crop acreages; livestock breeds; herd sizes; harvest, tillage, and manure handling strategies; equipment and structures; and planting and harvesting dates.

Appendix 6: Projected habitat maps for Pennsylvania for 36 tree species

Acknowledgement: These maps were created by Louis Iverson, Prasad, Matthews, and Matthew Peters for the Union of Concerned Scientists. The maps were provided to the author by Melanie Kirkpatrick from the Union of Concerned Scientists. Permission to reproduce them here was obtained from Louis Iverson and the Union of Concerned Scientists.

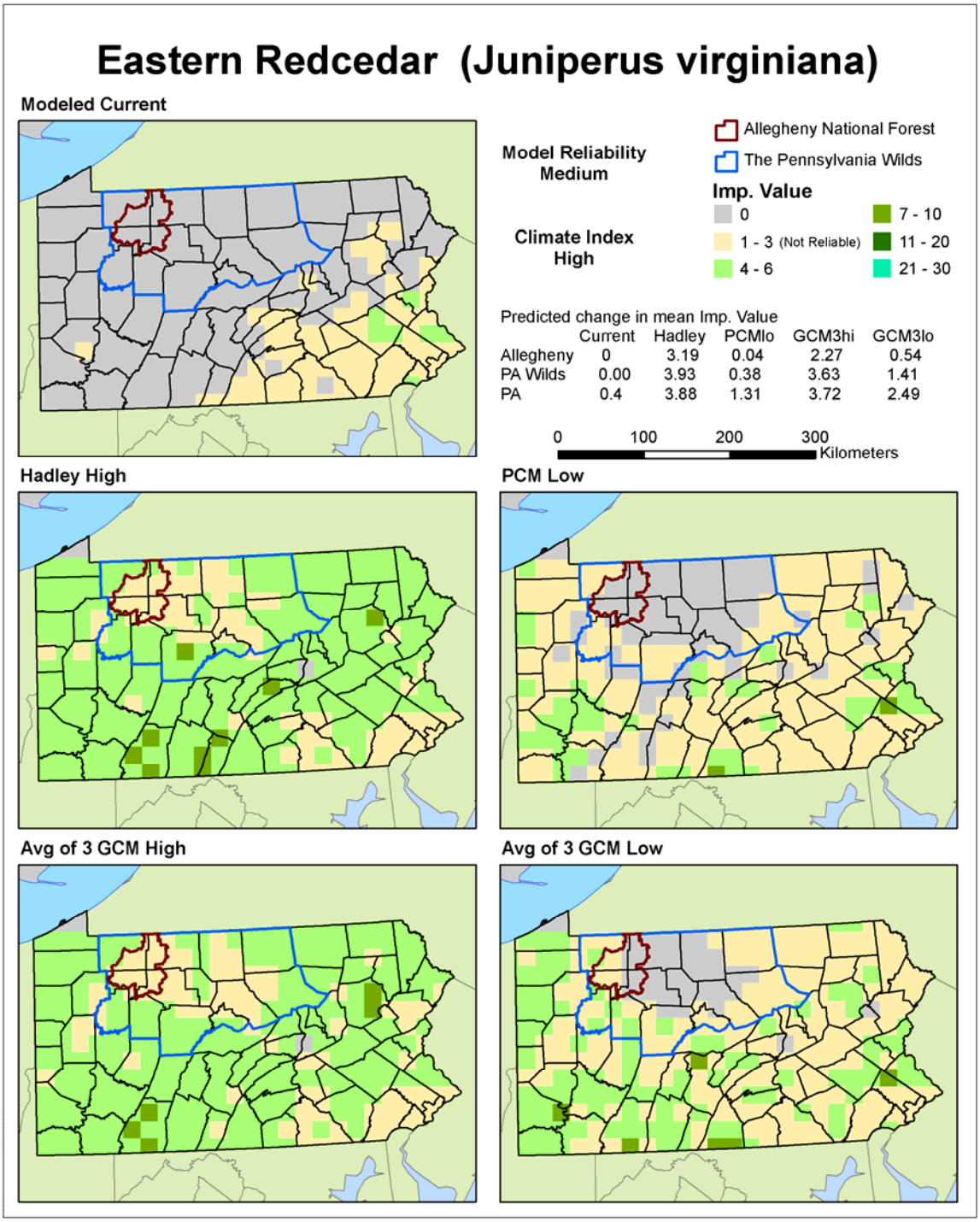

Figure A.6.1 Current modeled area-weighted habitat importance values for eastern red cedar in Pennsylvania and projected 2100 importance values under four climate change scenarios.

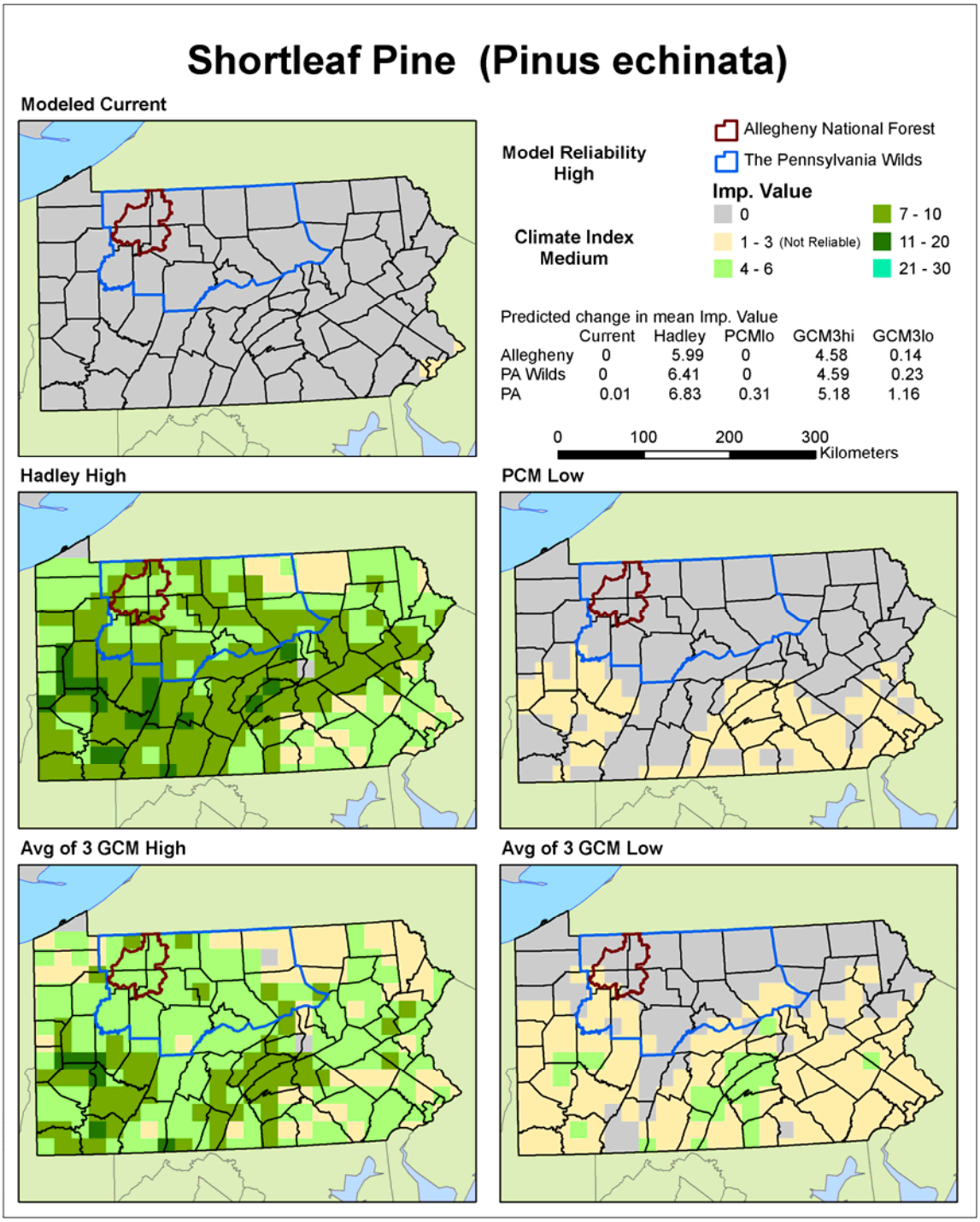

Figure A.6.2 Current modeled area-weighted habitat importance values for shortleaf pine in Pennsylvania and projected 2100 importance values under four climate change scenarios.

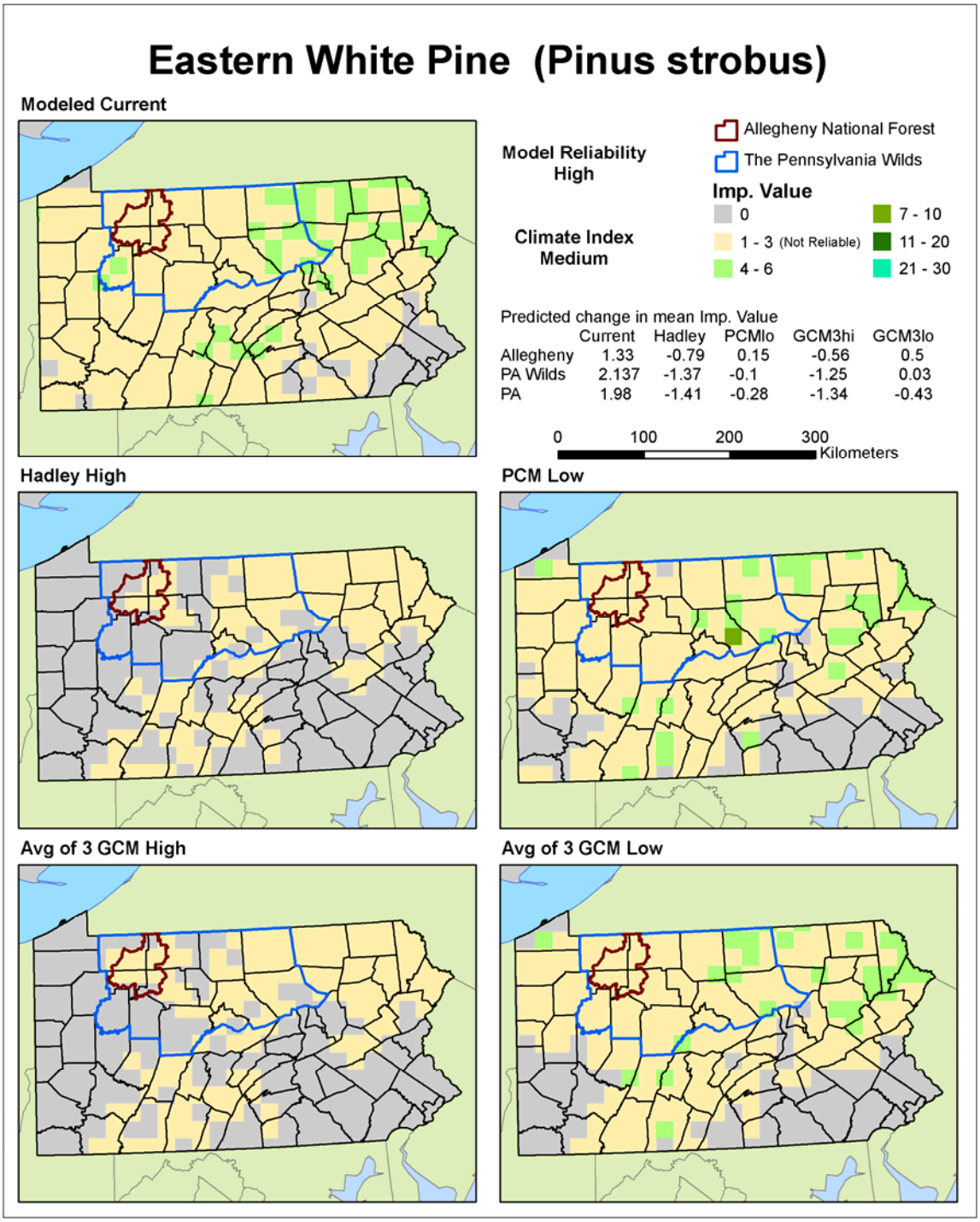

Figure A.6.3 Current modeled area-weighted habitat importance values for eastern white pine in Pennsylvania and projected 2100 importance values under four climate change scenarios.

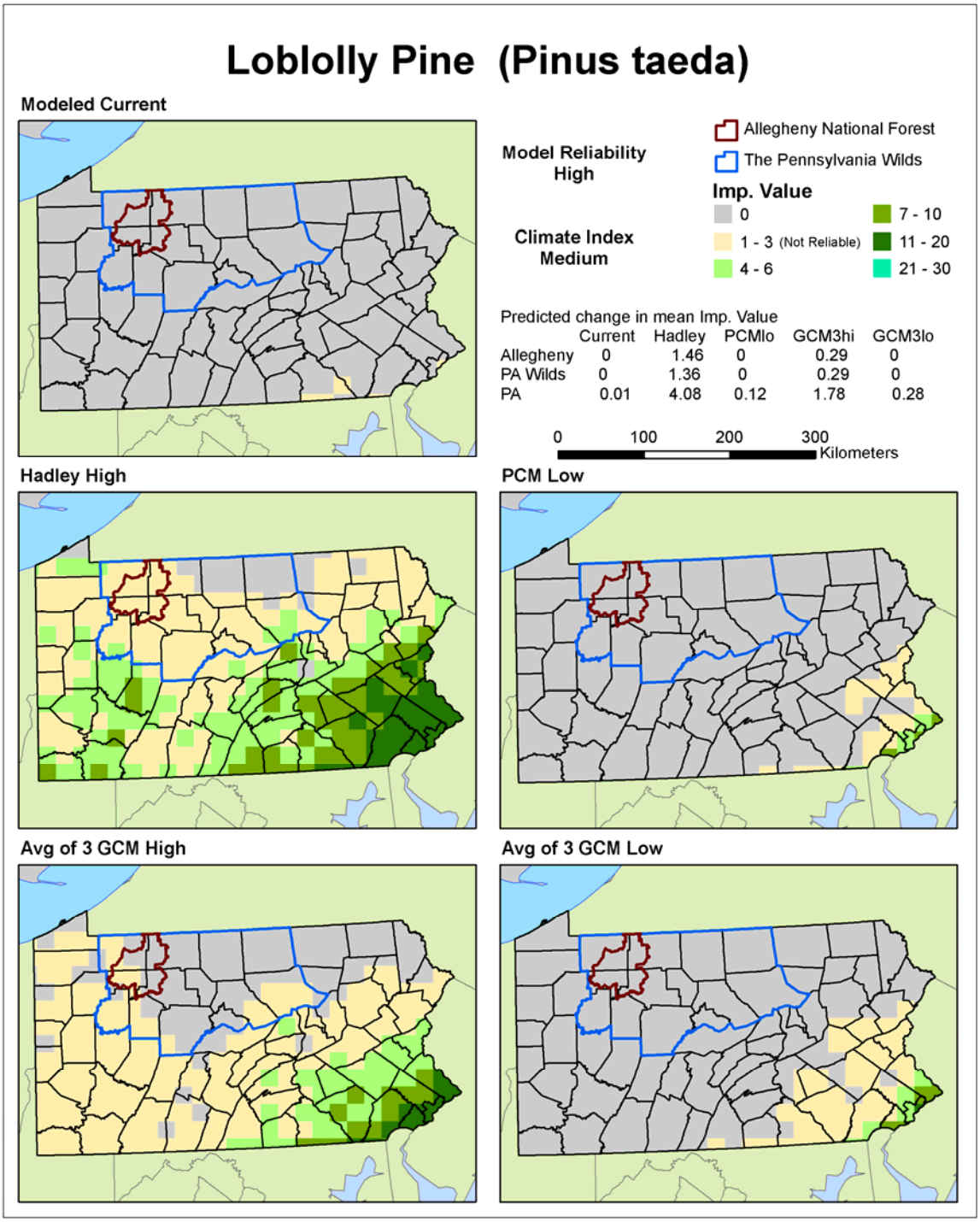

Figure A.6.4 Current modeled area-weighted habitat importance values for loblolly pine in Pennsylvania and projected 2100 importance values under four climate change scenarios.

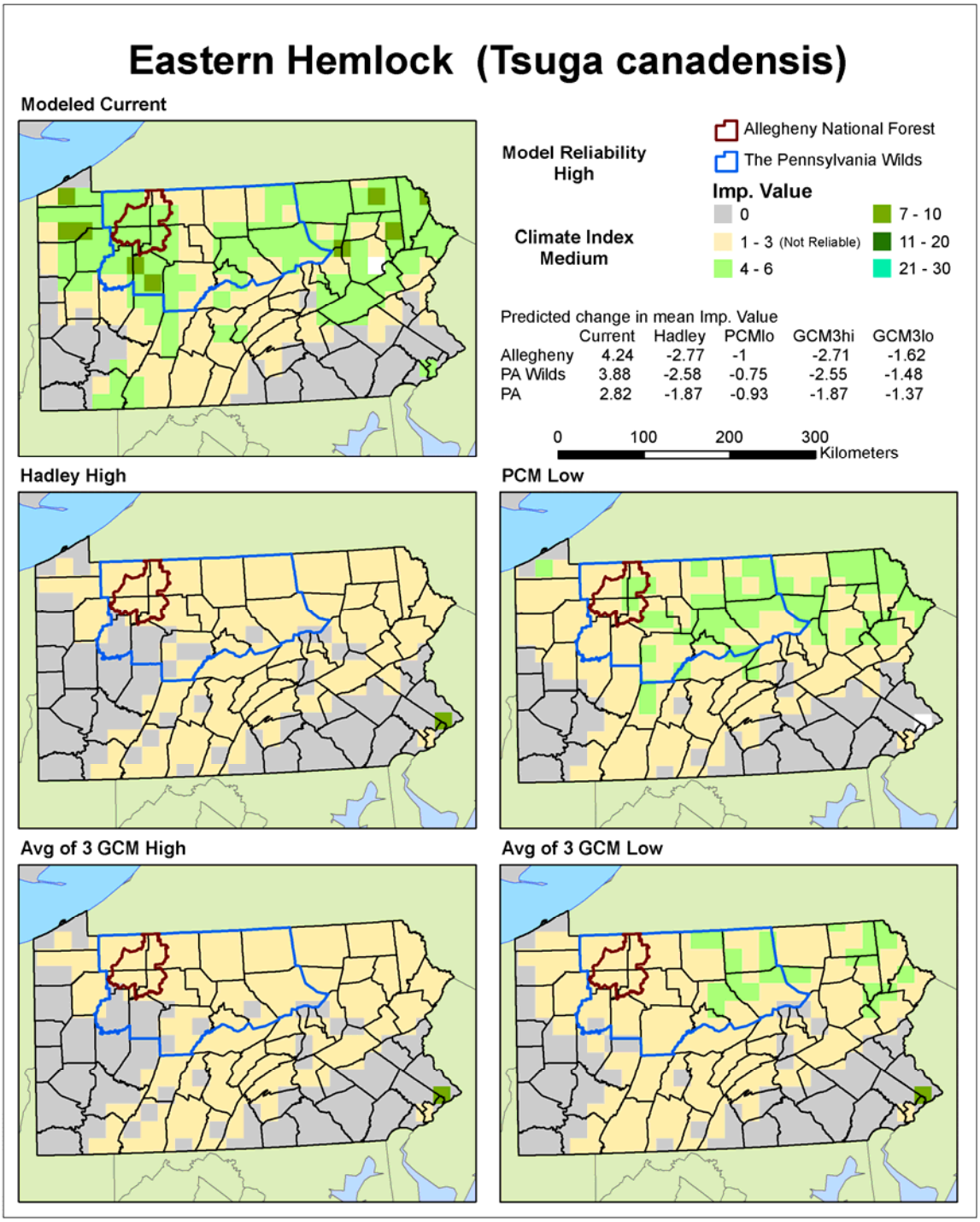

Figure A.6.5 Current modeled area-weighted habitat importance values for eastern hemlock in Pennsylvania and projected 2100 importance values under four climate change scenarios.

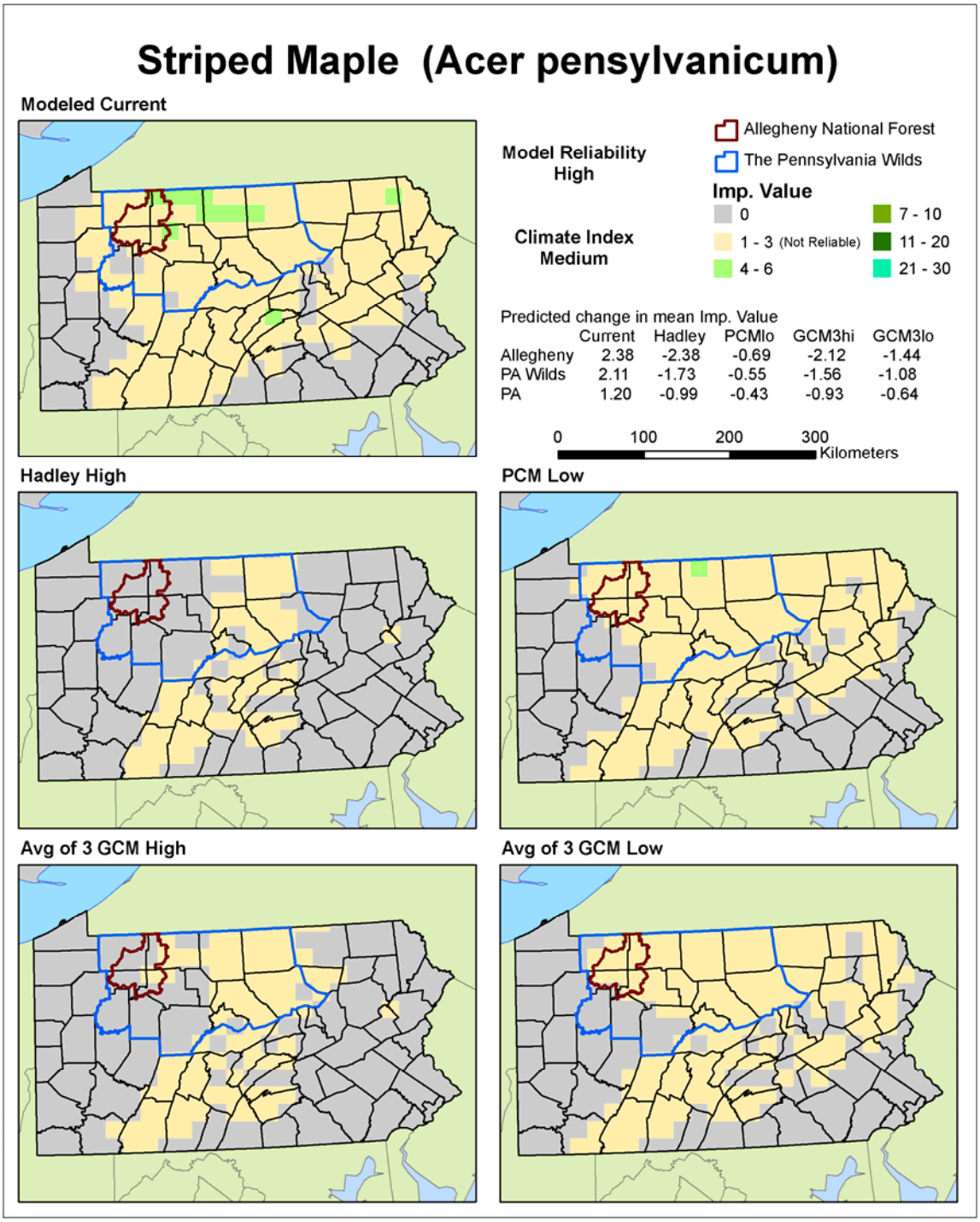

Figure A.6.6 Current modeled area-weighted habitat importance values for striped maple in Pennsylvania and projected 2100 importance values under four climate change scenarios.

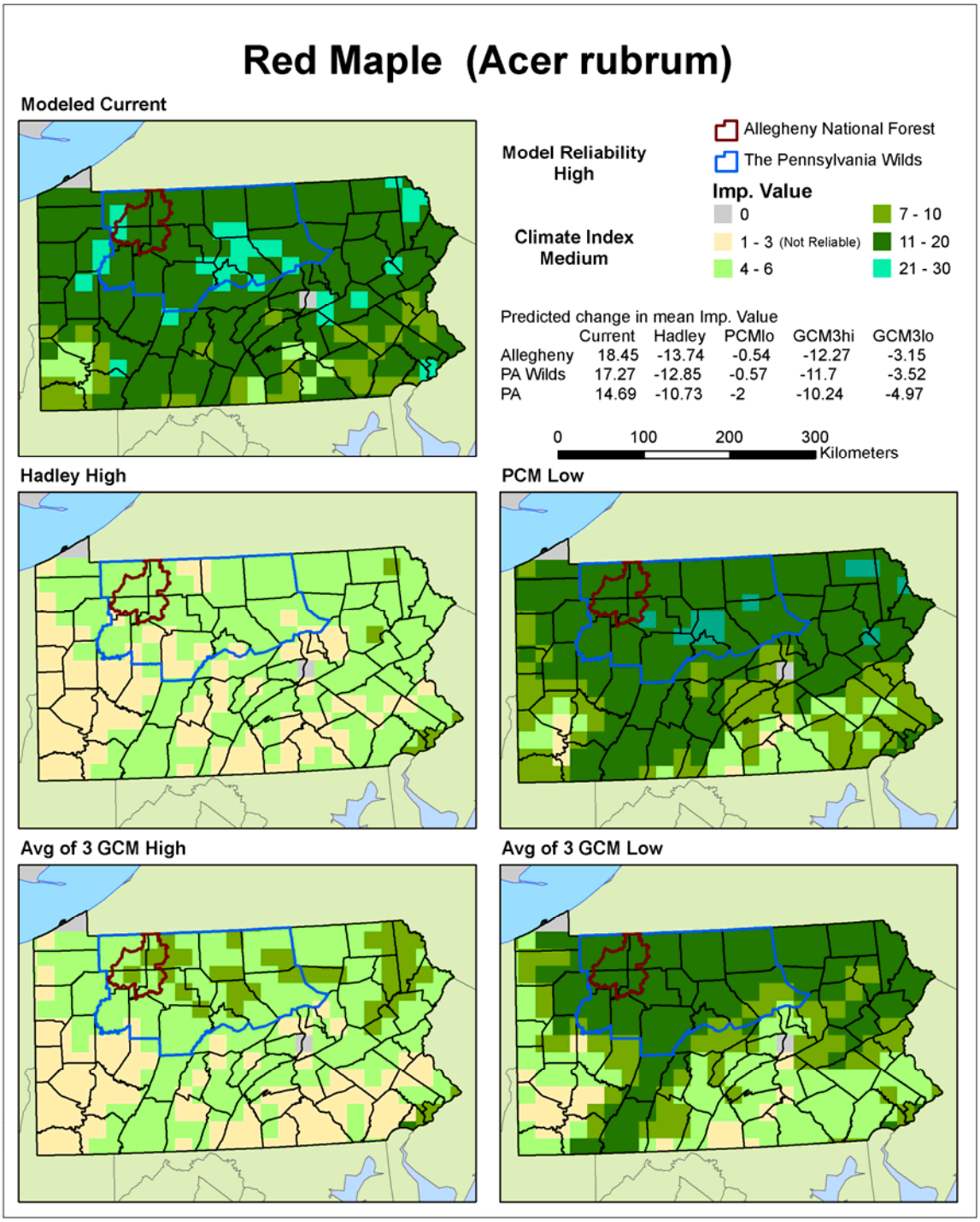

Figure A.6.7 Current modeled area-weighted habitat importance values for red maple in Pennsylvania and projected 2100 importance values under four climate change scenarios.

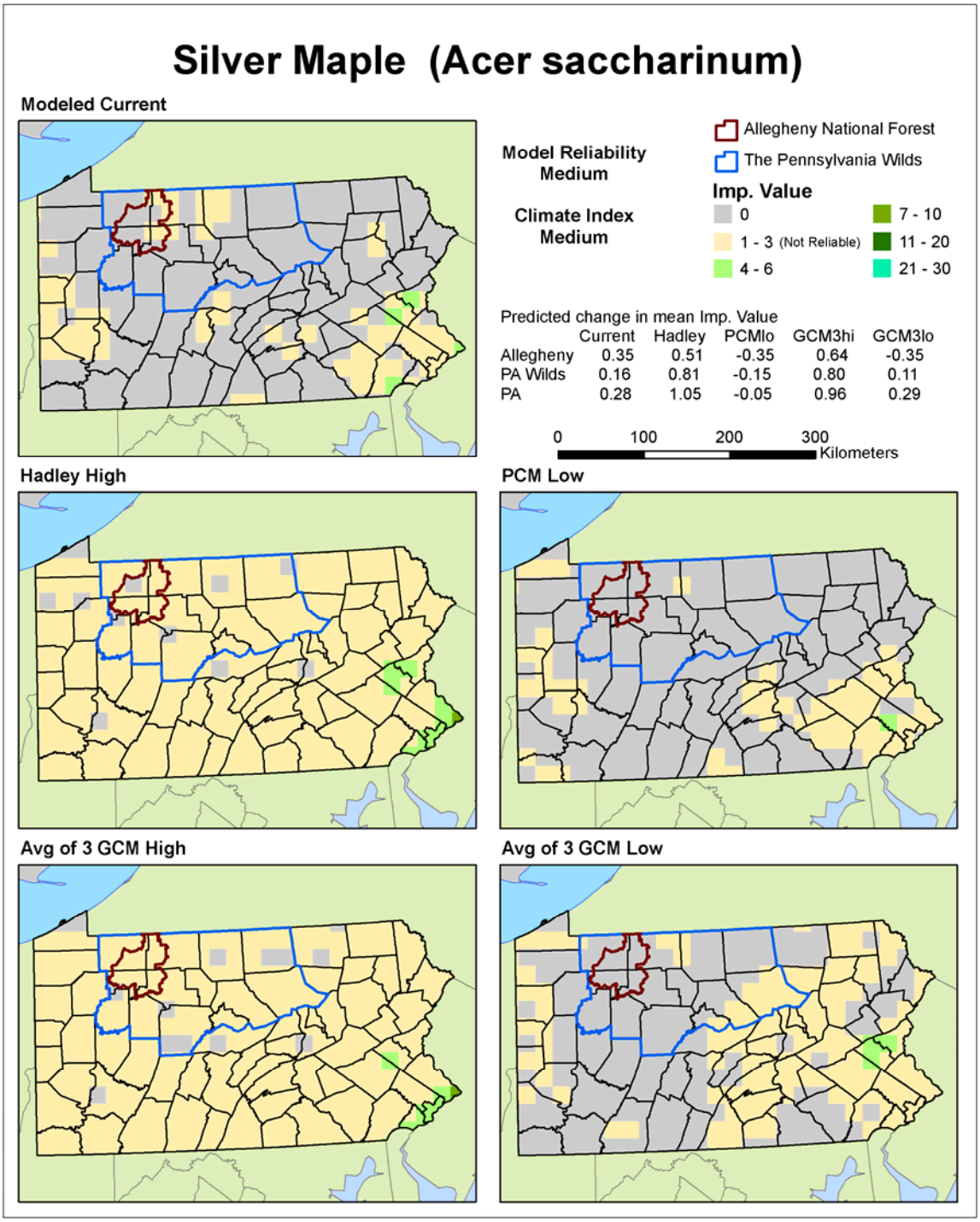

Figure A.6.8 Current modeled area-weighted habitat importance values for silver maple in Pennsylvania and projected 2100 importance values under four climate change scenarios.

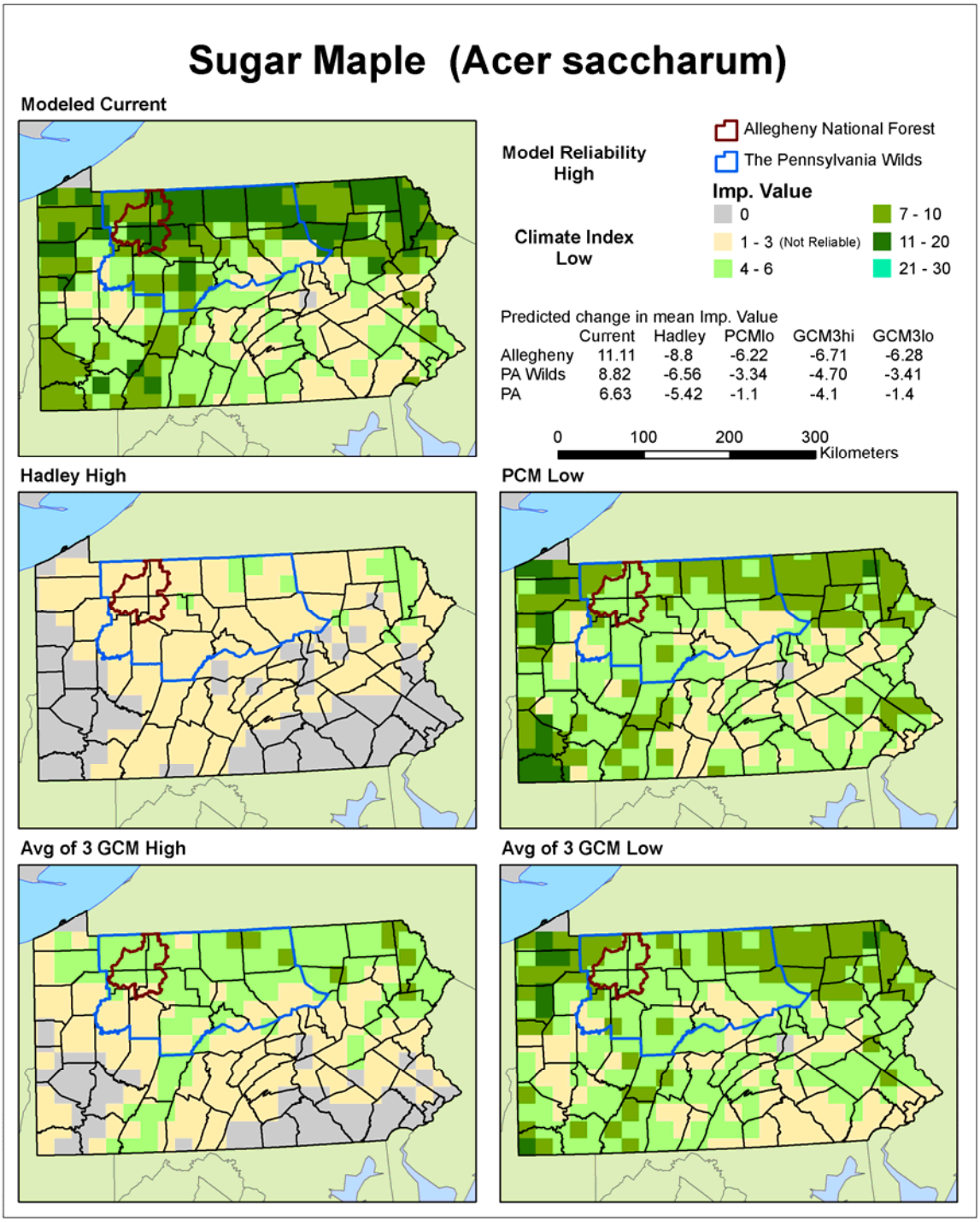

Figure A.6.9 Current modeled area-weighted habitat importance values for sugar maple in Pennsylvania and projected 2100 importance values under four climate change scenarios.

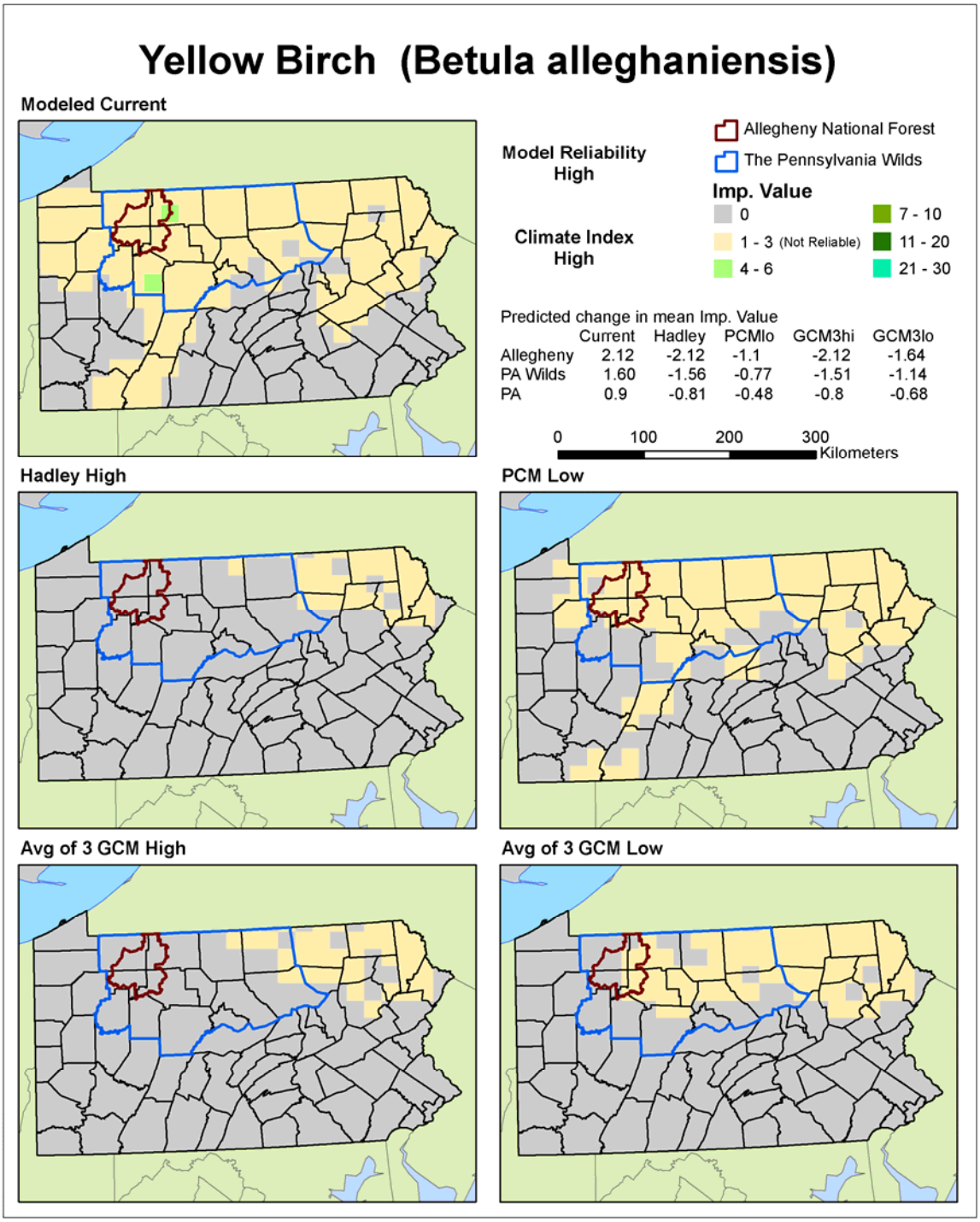

Figure A.6.10 Current modeled area-weighted habitat importance values for yellow birch in Pennsylvania and projected 2100 importance values under four climate change scenarios.

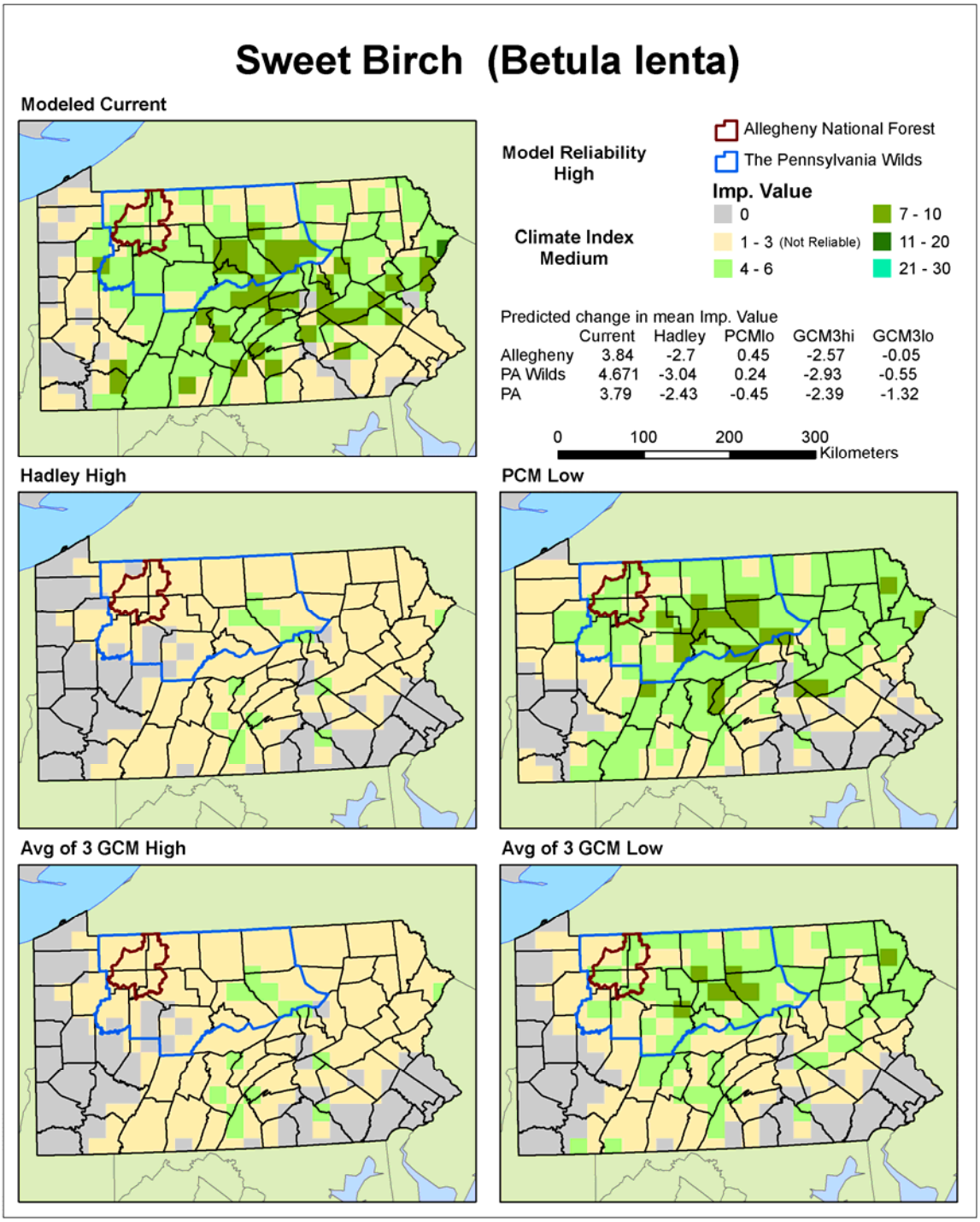

Figure A.6.11 Current modeled area-weighted habitat importance values for sweet birch (aka black birch) in Pennsylvania and projected 2100 importance values under four climate change scenarios.

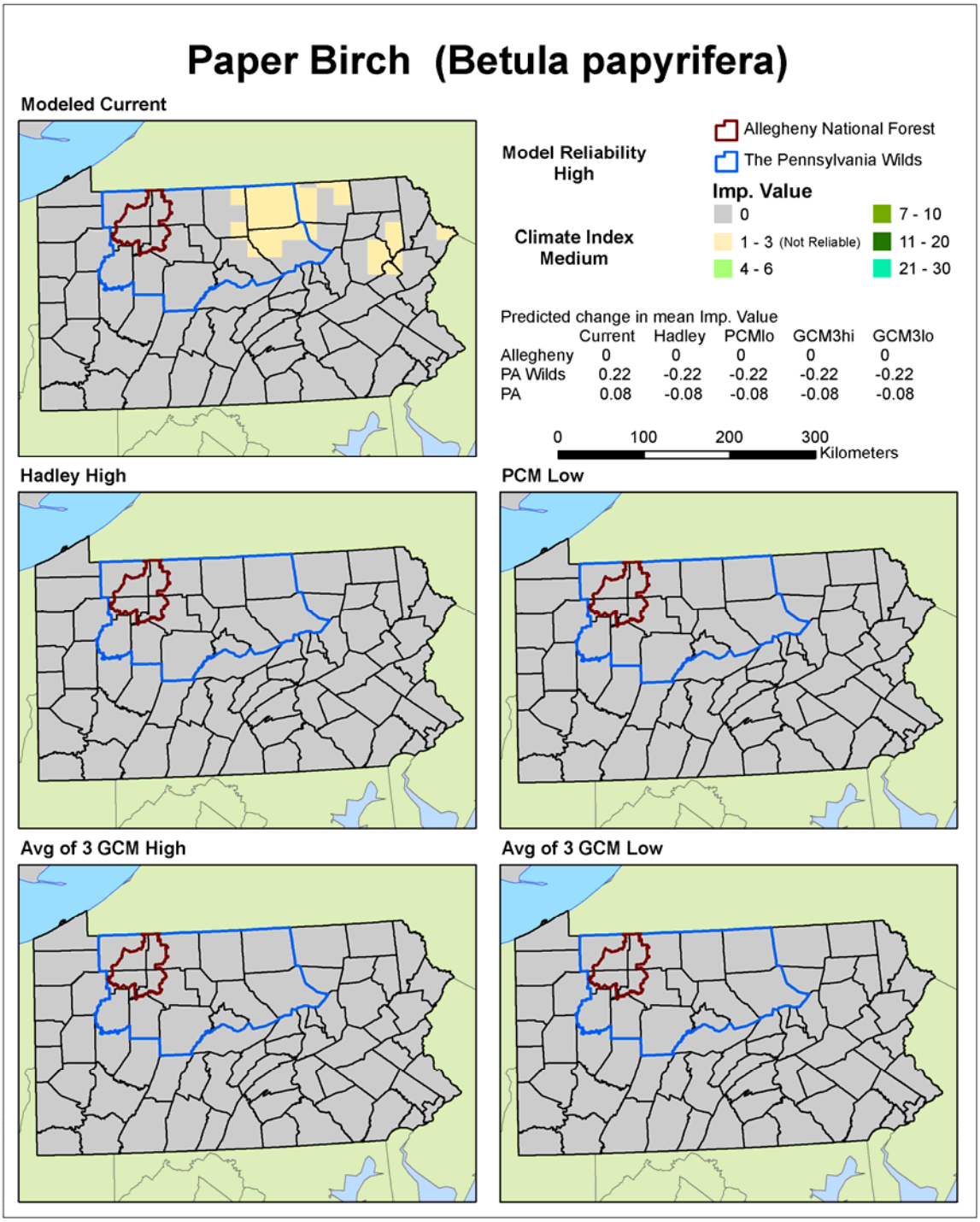

Figure A.6.12 Current modeled area-weighted habitat importance values for paper birch in Pennsylvania and projected 2100 importance values under four climate change scenarios.

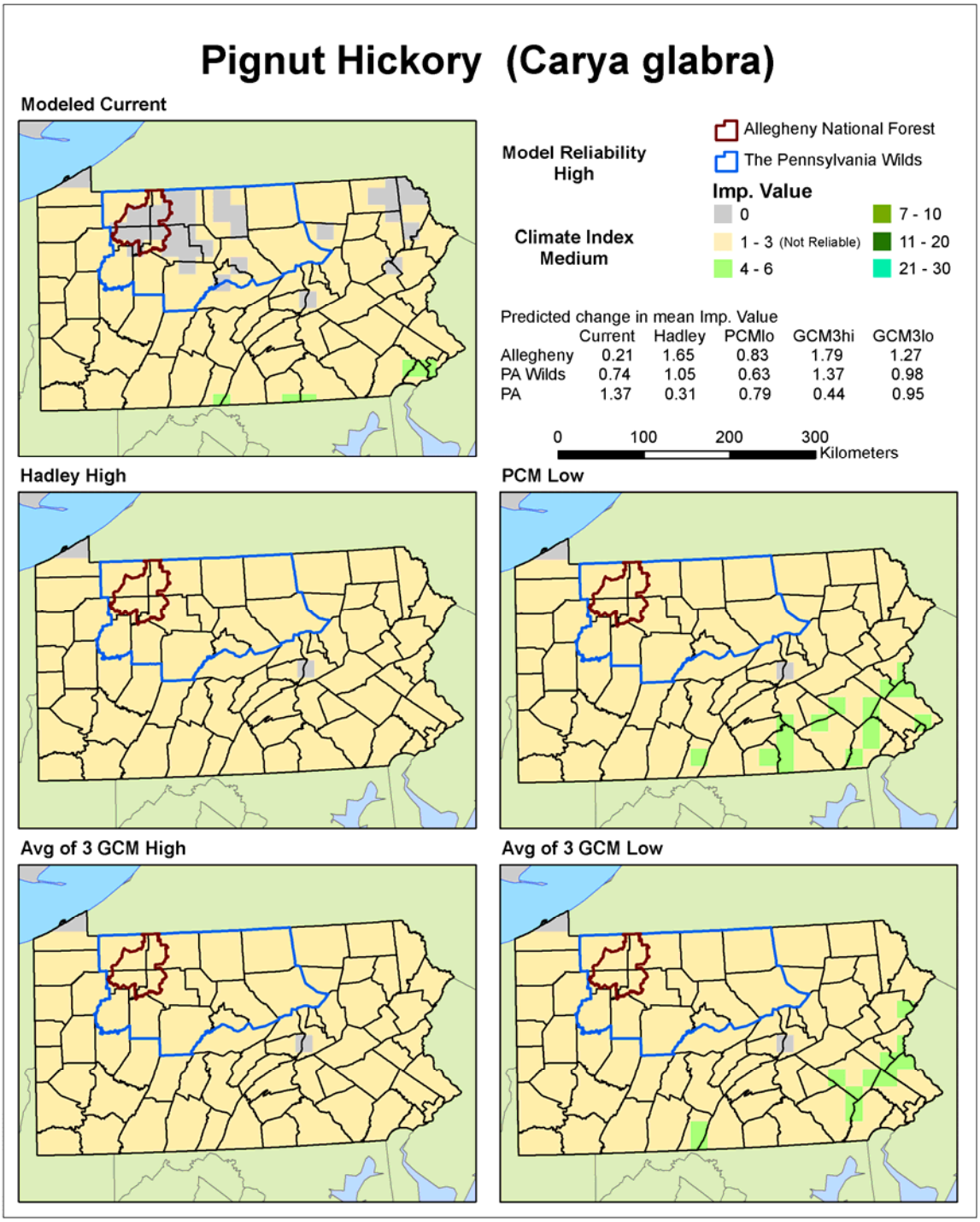

Figure A.6.13 Current modeled area-weighted habitat importance values for pignut hickory in Pennsylvania and projected 2100 importance values under four climate change scenarios.

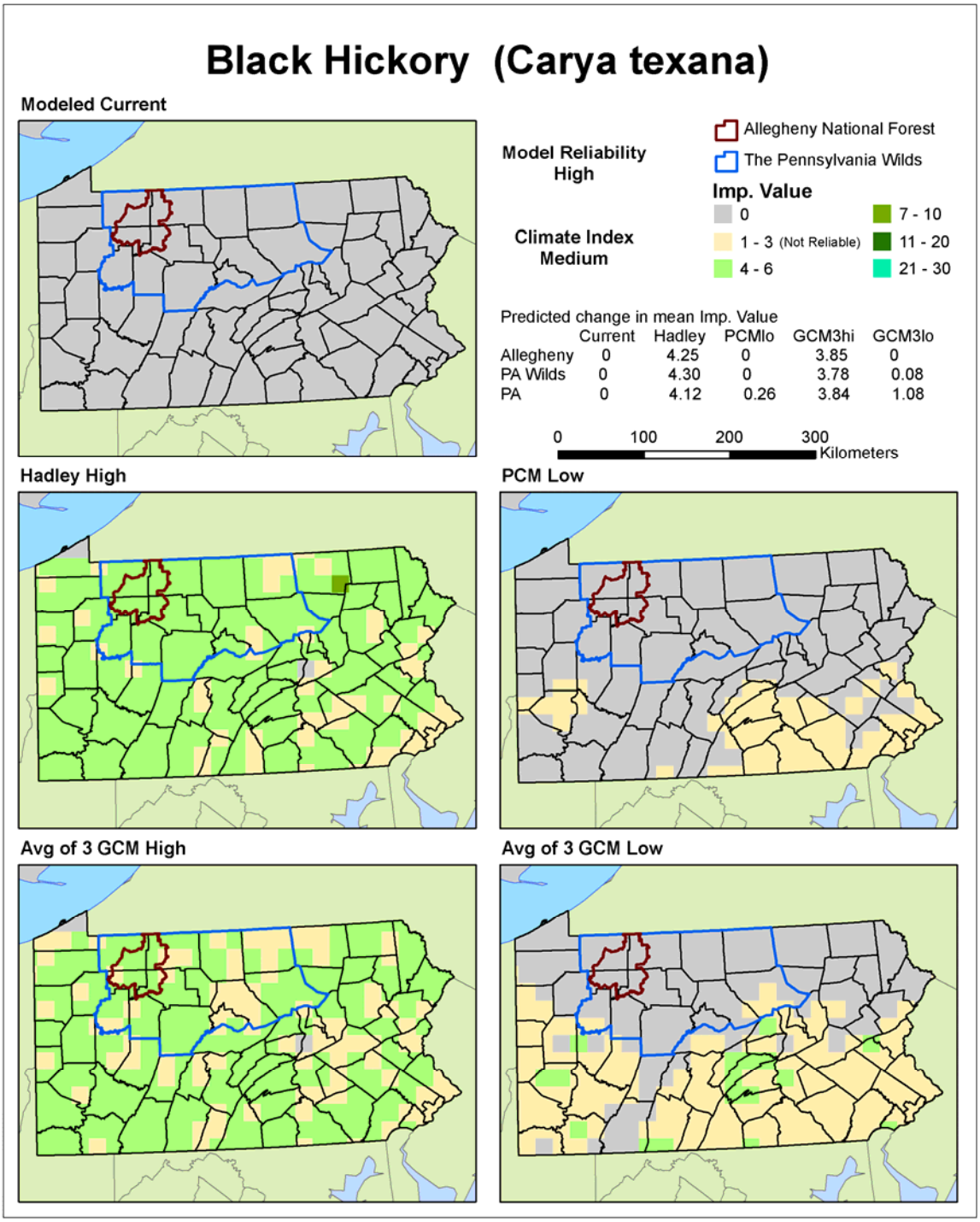

Figure A.6.14 Current modeled area-weighted habitat importance values for black hickory in Pennsylvania and projected 2100 importance values under four climate change scenarios.

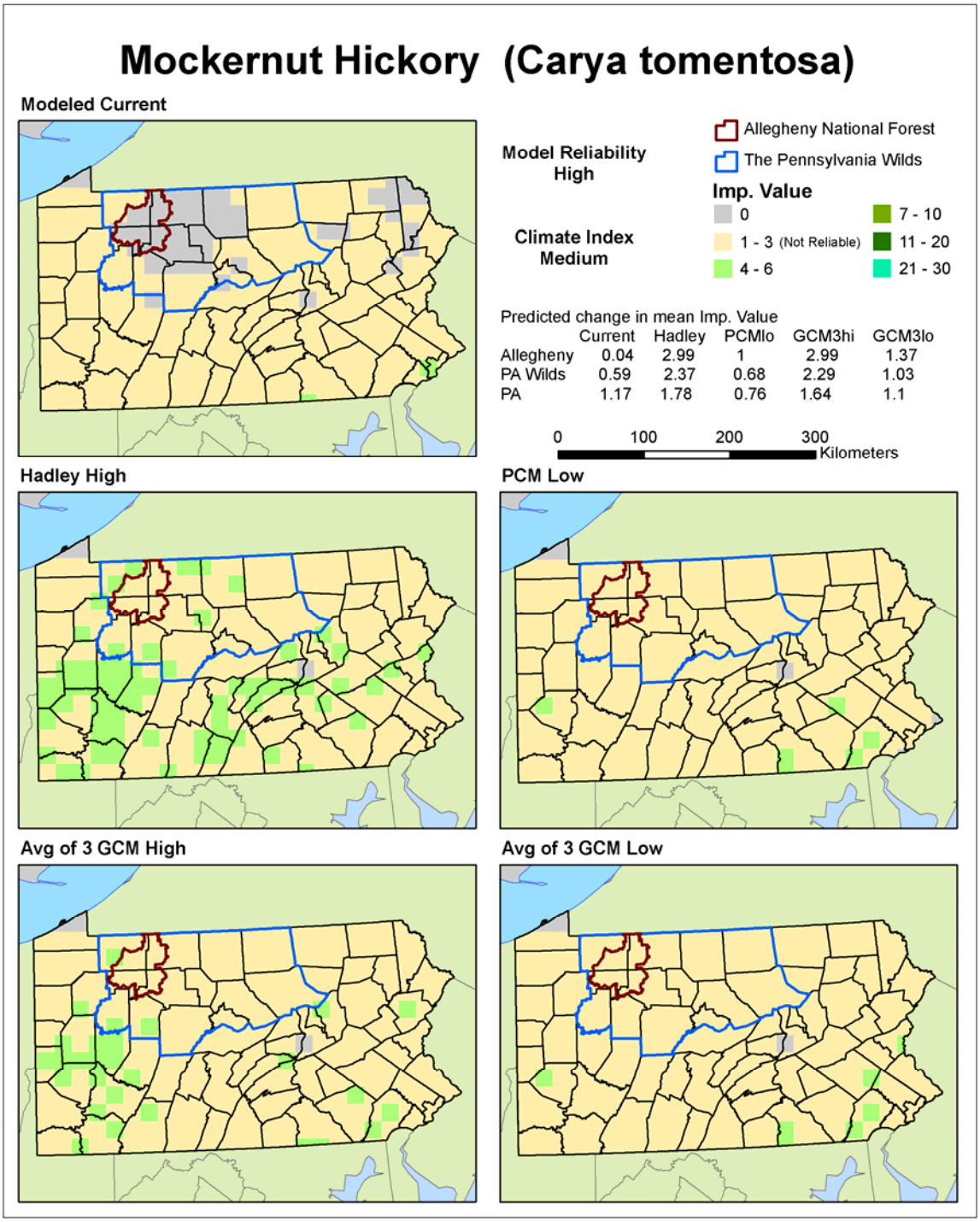

Figure A.6.15 Current modeled area-weighted habitat importance values for mockernut hickory in Pennsylvania and projected 2100 importance values under four climate change scenarios.

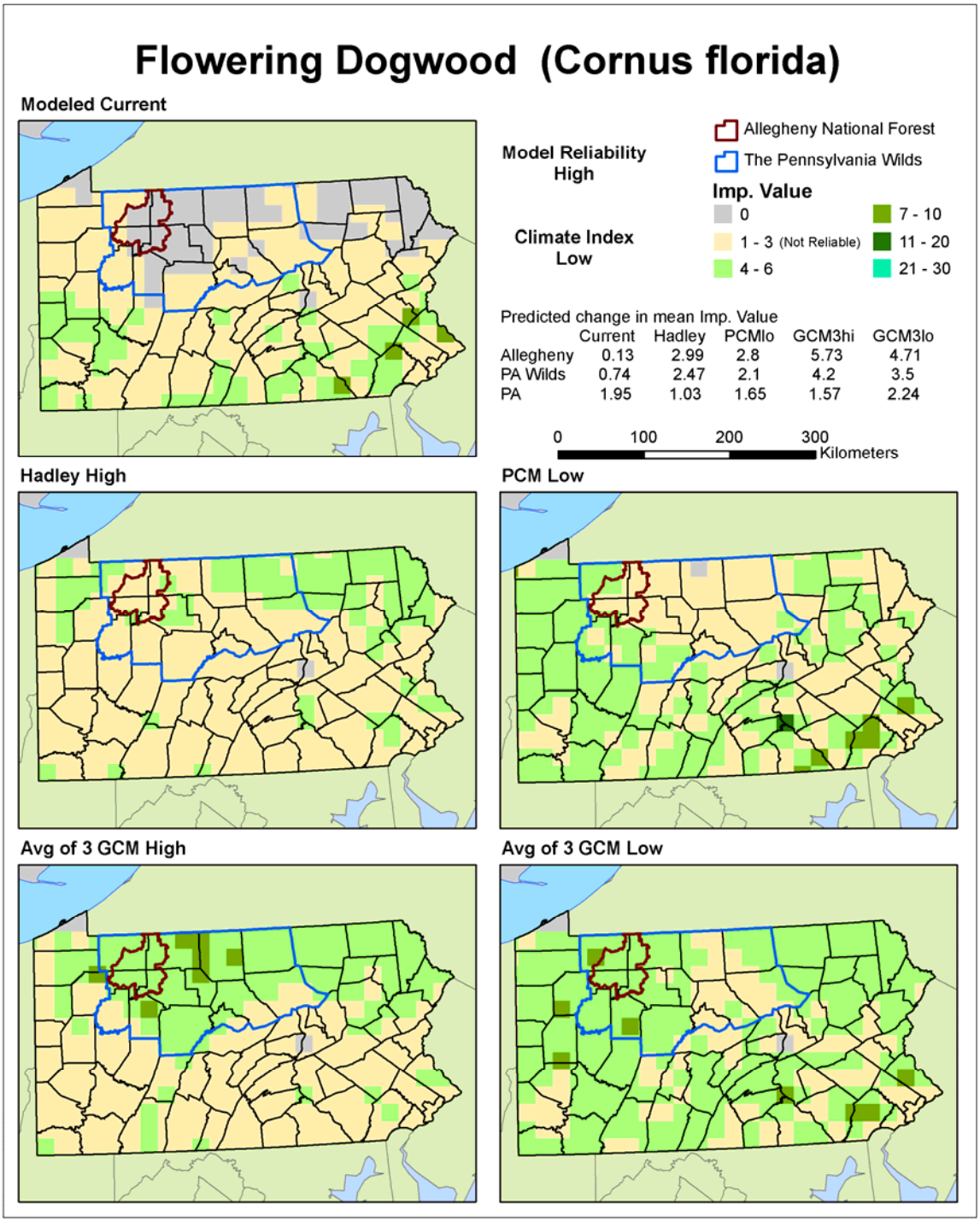

Figure A.6.16 Current modeled area-weighted habitat importance values for flowering dogwood in Pennsylvania and projected 2100 importance values under four climate change scenarios.

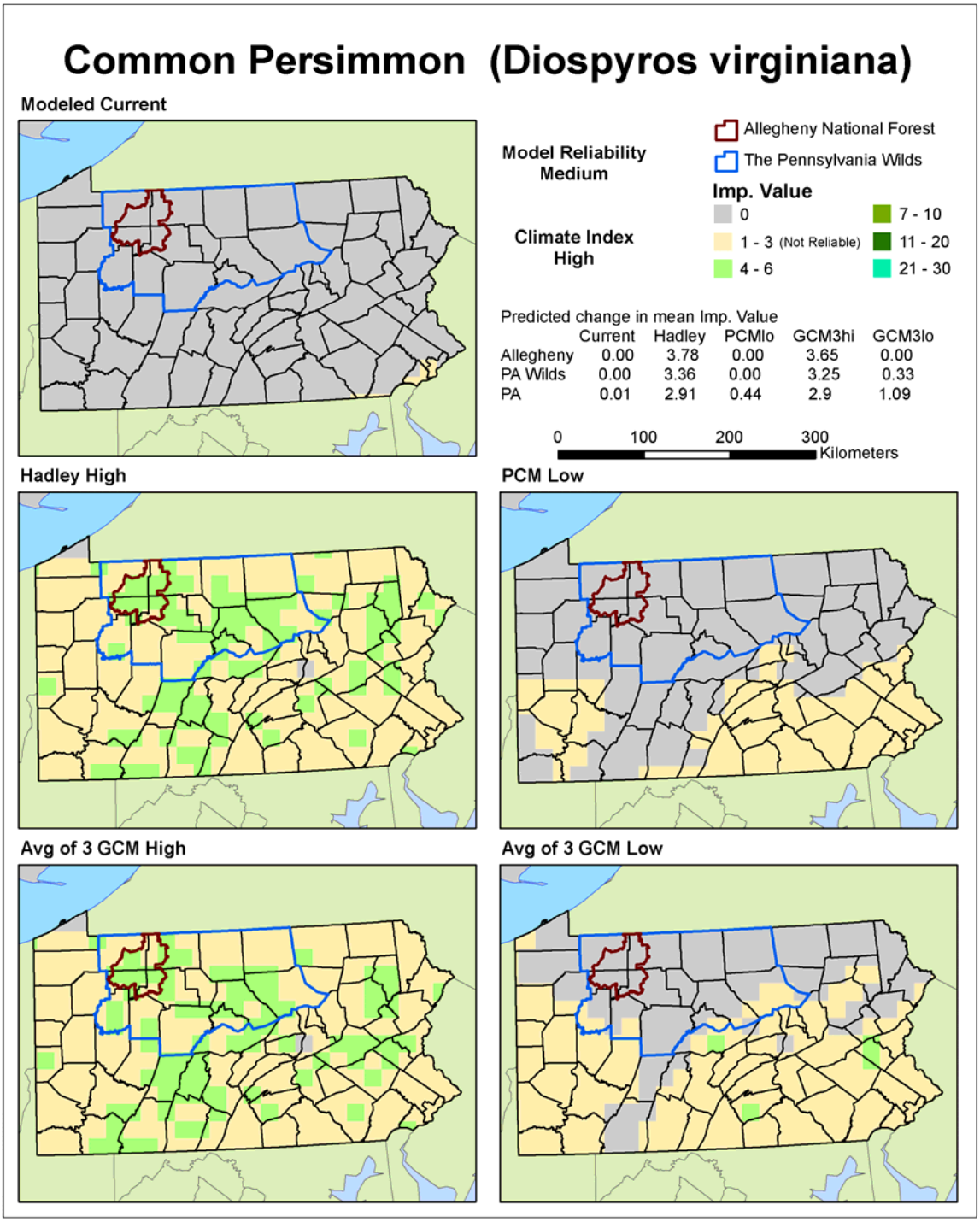

Figure A.6.17 Current modeled area-weighted habitat importance values for common persimmon in Pennsylvania and projected 2100 importance values under four climate change scenarios.

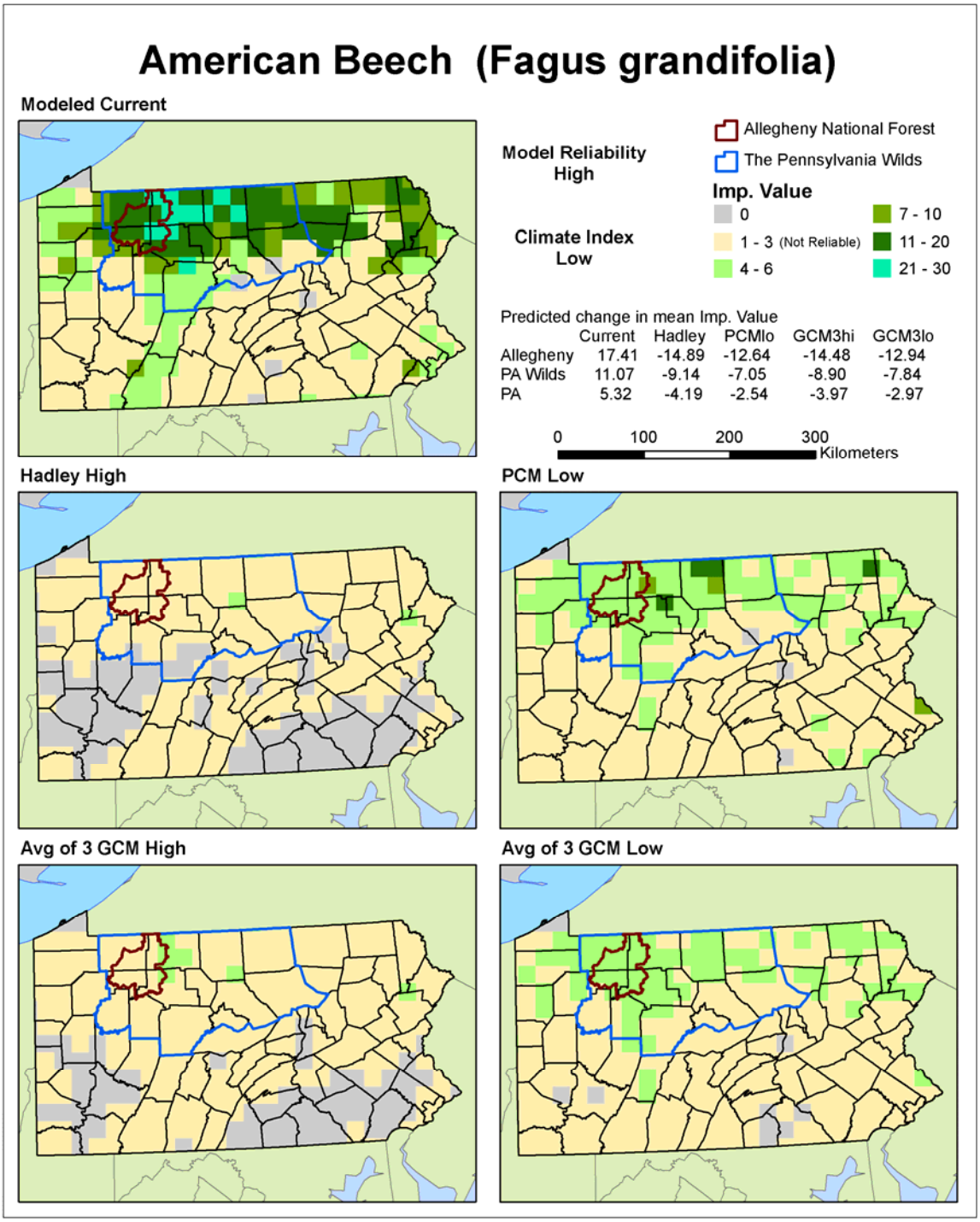

Figure A.6.18 Current modeled area-weighted habitat importance values for American beech in Pennsylvania and projected 2100 importance values under four climate change scenarios.

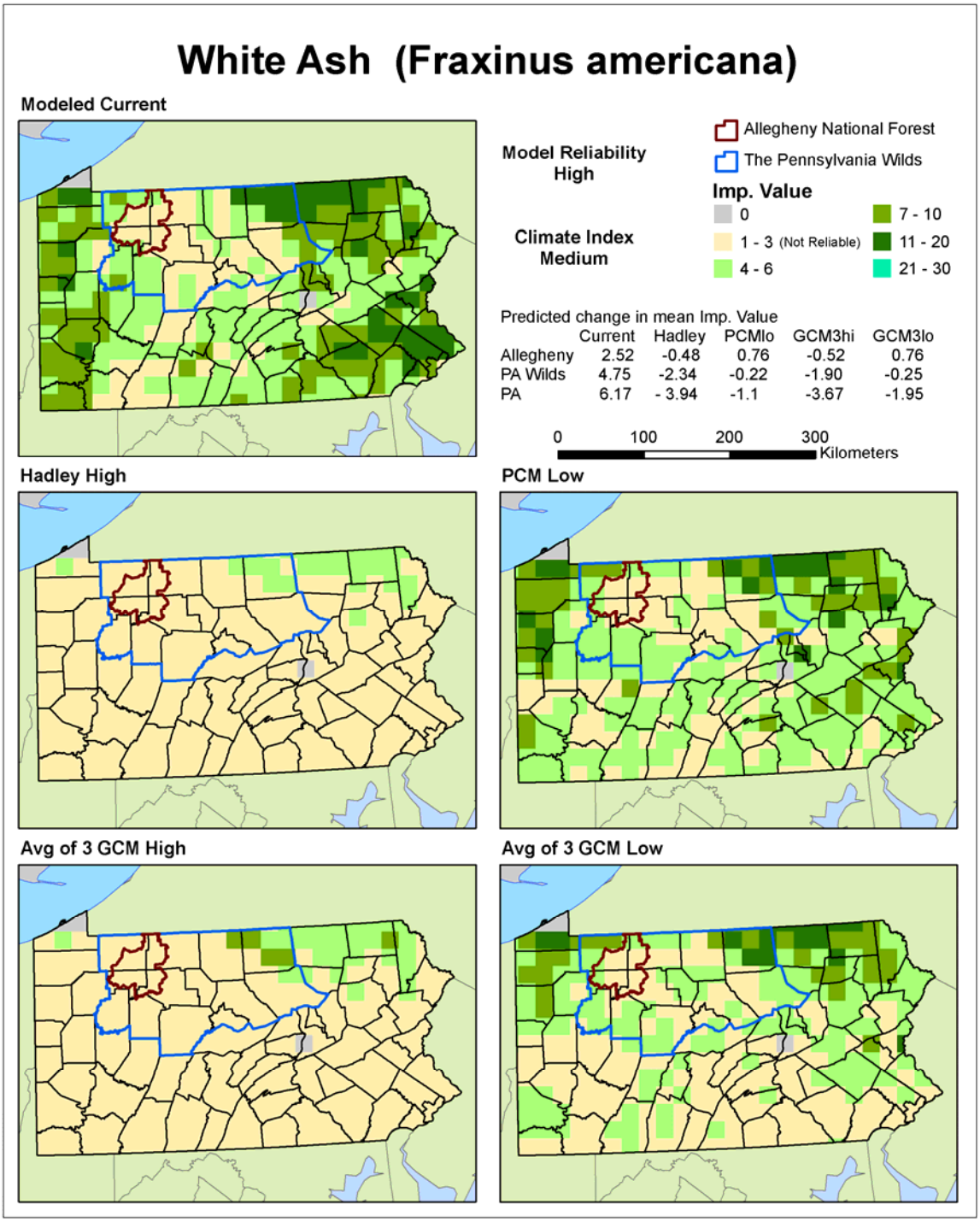

Figure A.6.19 Current modeled area-weighted habitat importance values for white ash in Pennsylvania and projected 2100 importance values under four climate change scenarios.

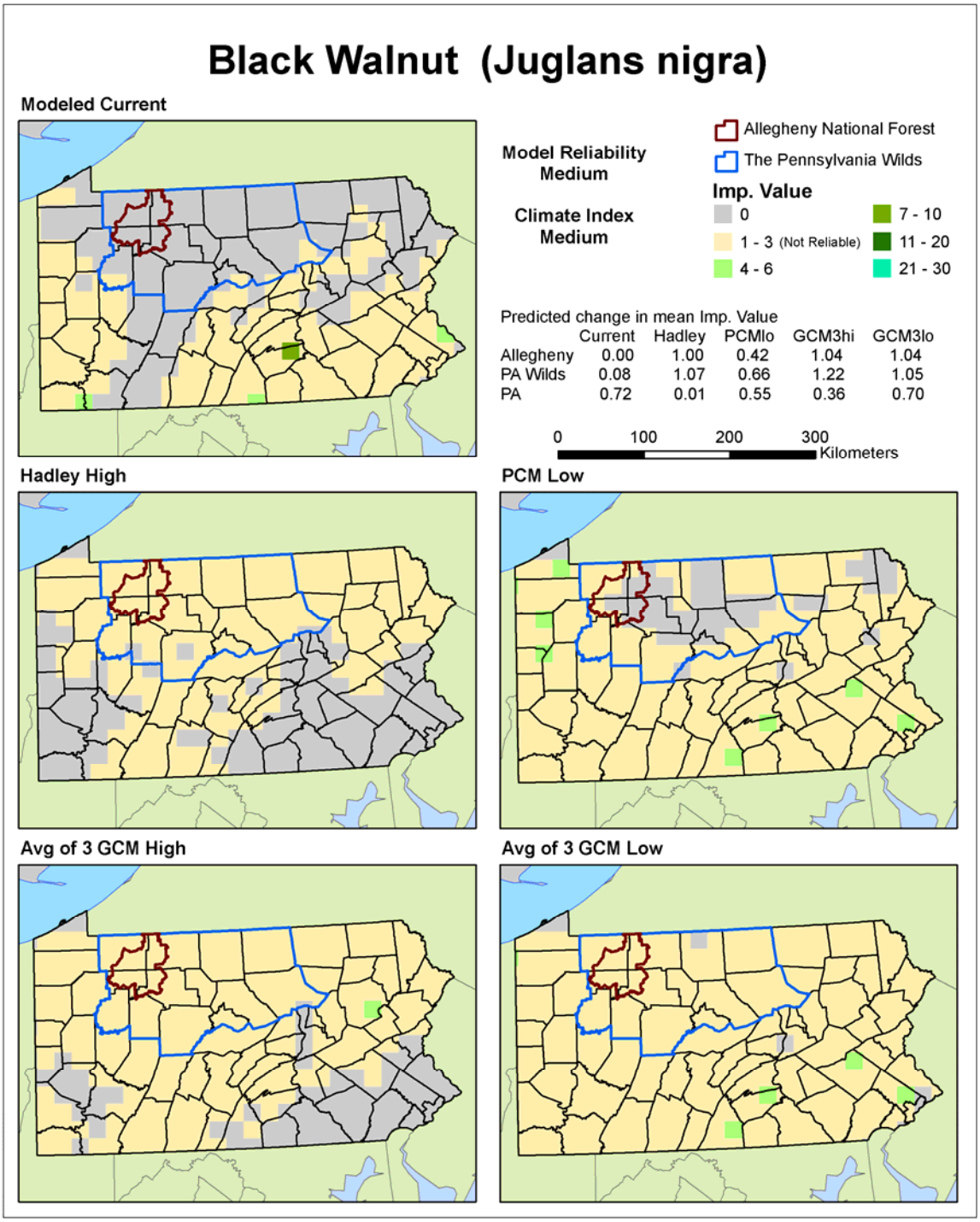

Figure A.6.20 Current modeled area-weighted habitat importance values for black walnut in Pennsylvania and projected 2100 importance values under four climate change scenarios.

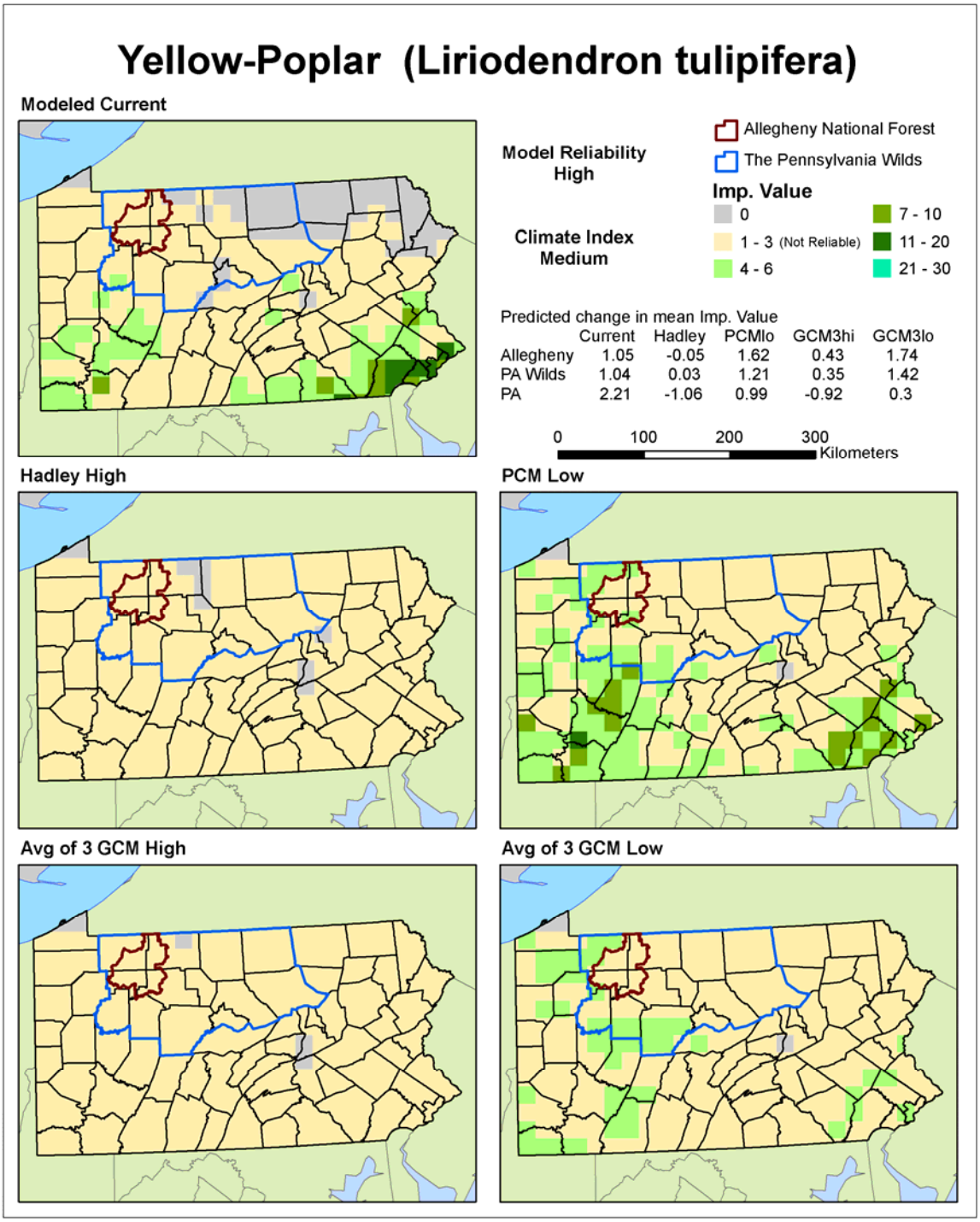

Figure A.6.21 Current modeled area-weighted habitat importance values for yellow-poplar in Pennsylvania and projected 2100 importance values under four climate change scenarios.

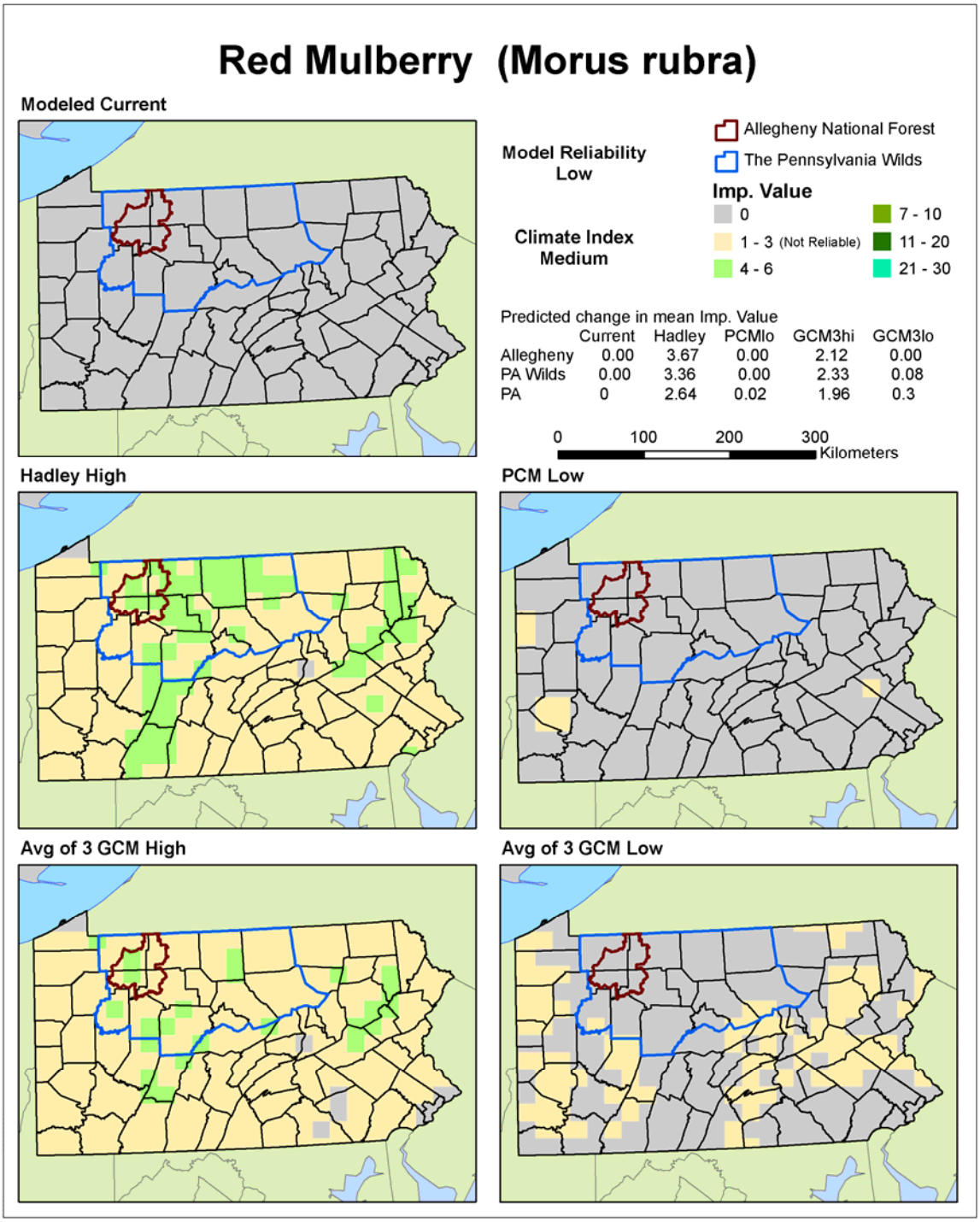

Figure A.6.22 Current modeled area-weighted habitat importance values for red mulberry in Pennsylvania and projected 2100 importance values under four climate change scenarios.

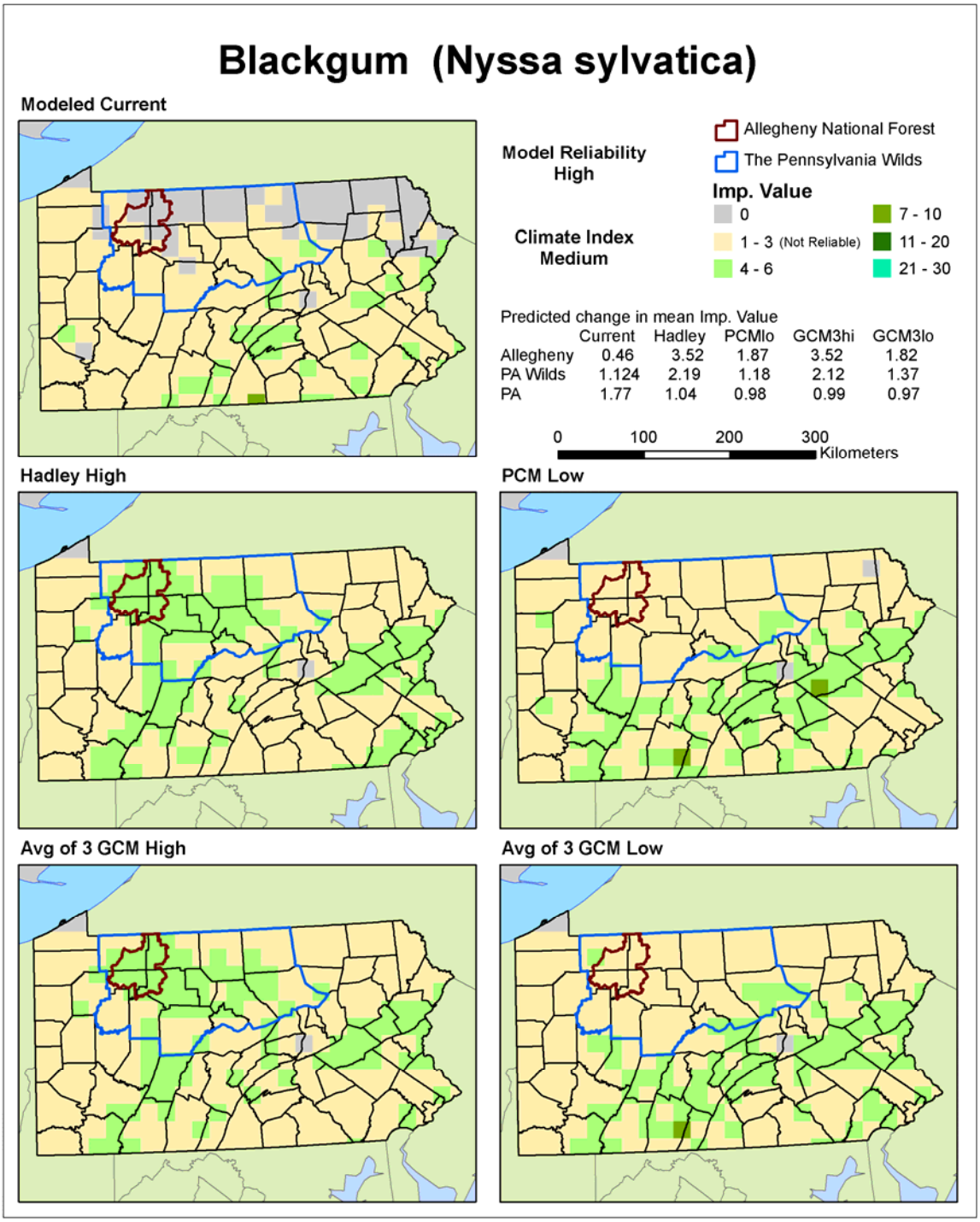

Figure A.6.23 Current modeled area-weighted habitat importance values for blackgum in Pennsylvania and projected 2100 importance values under four climate change scenarios.

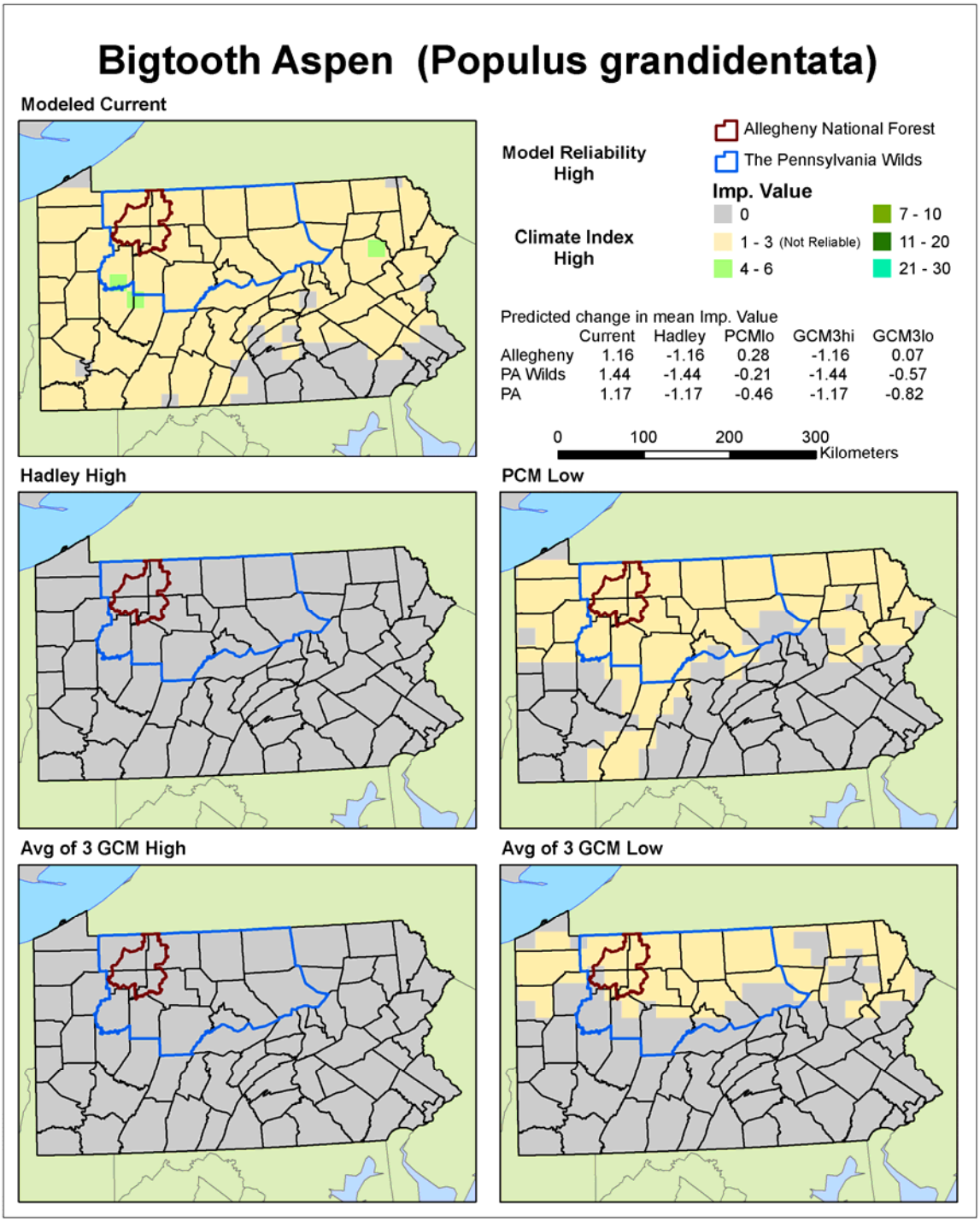

Figure A.6.24 Current modeled area-weighted habitat importance values for bigtooth aspen in Pennsylvania and projected 2100 importance values under four climate change scenarios.

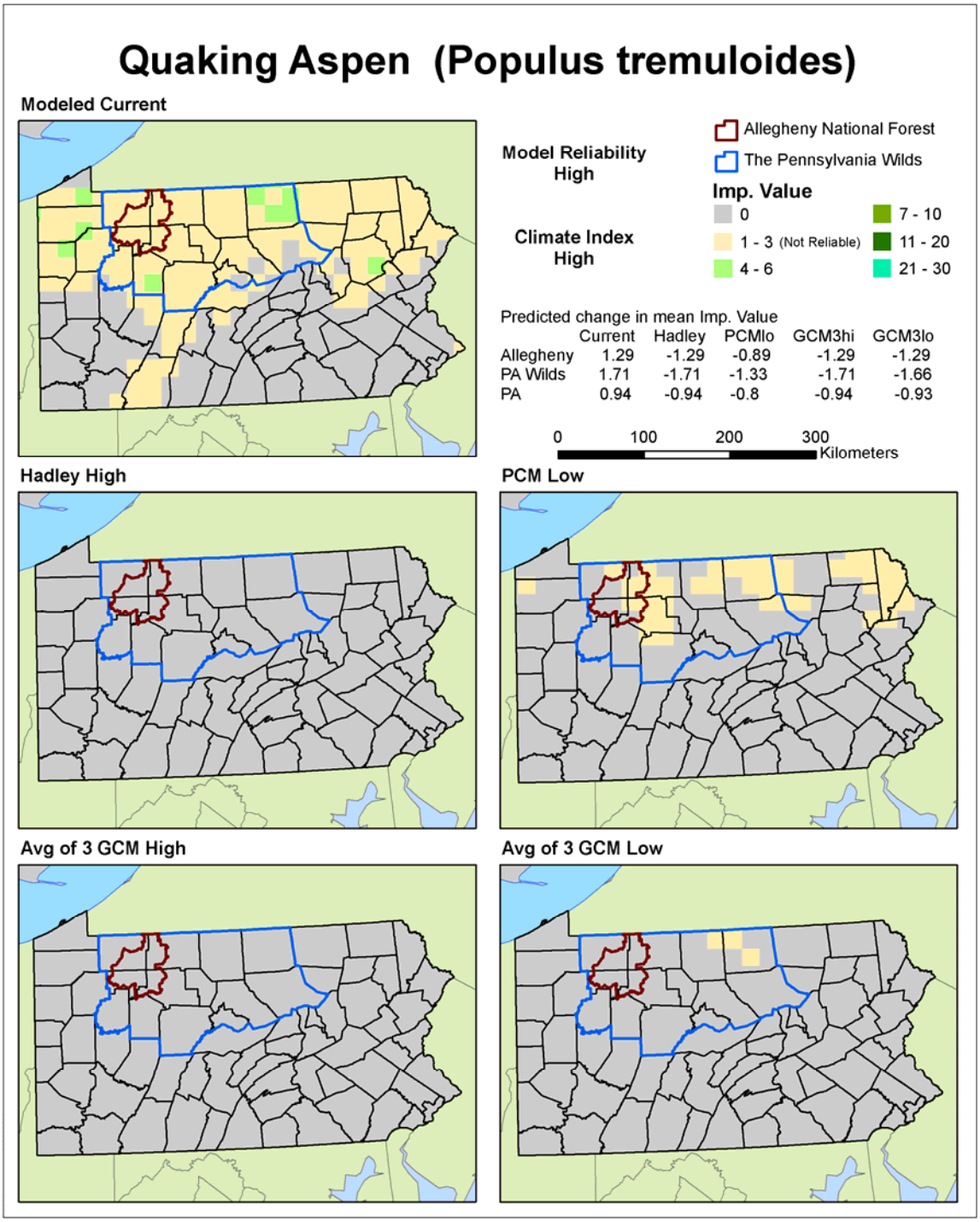

Figure A.6.25 Current modeled area-weighted habitat importance values for quaking aspen in Pennsylvania and projected 2100 importance values under four climate change scenarios.

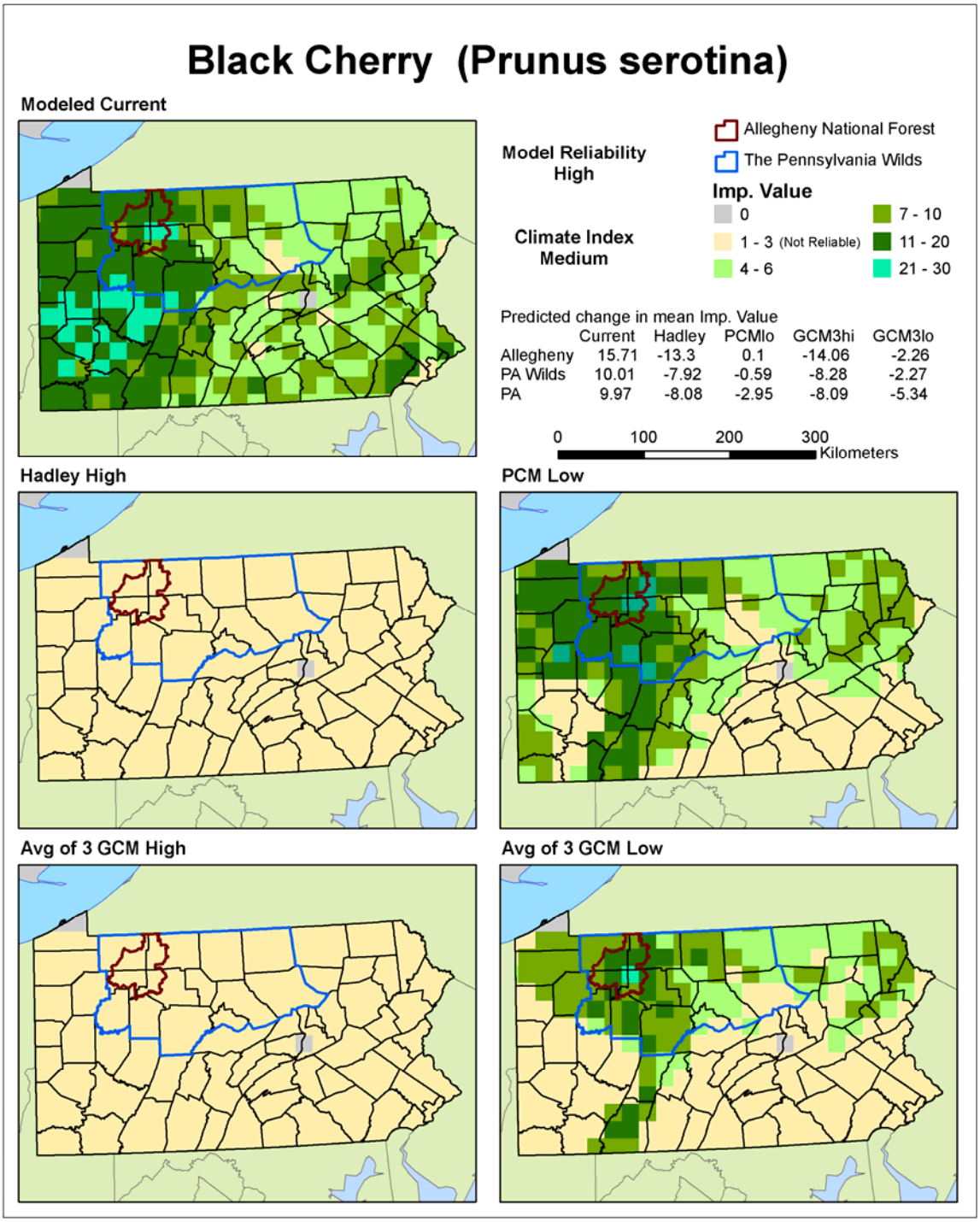

Figure A.6.26 Current modeled area-weighted habitat importance values for black cherry in Pennsylvania and projected 2100 importance values under four climate change scenarios.

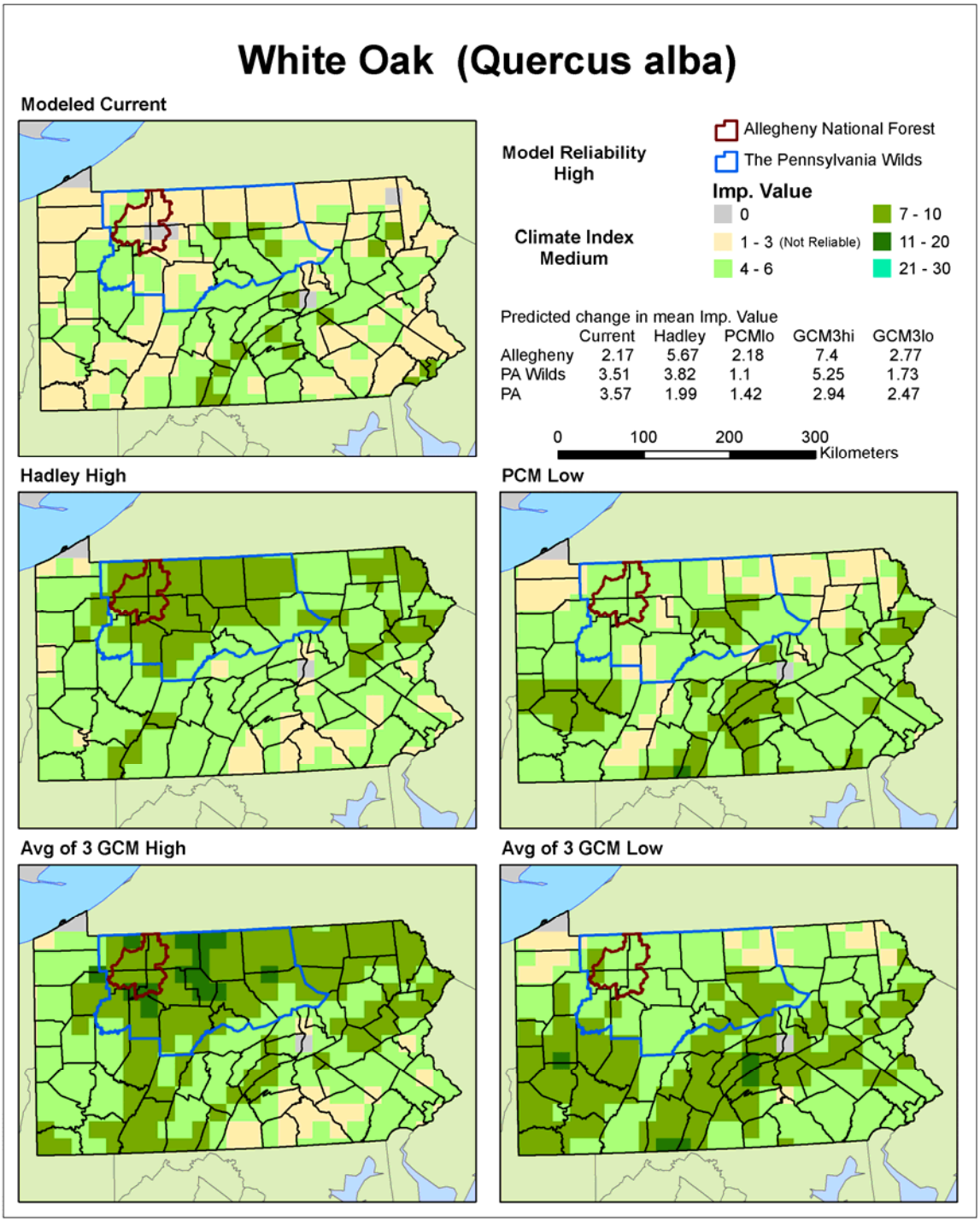

Figure A.6.27 Current modeled area-weighted habitat importance values for white oak in Pennsylvania and projected 2100 importance values under four climate change scenarios.

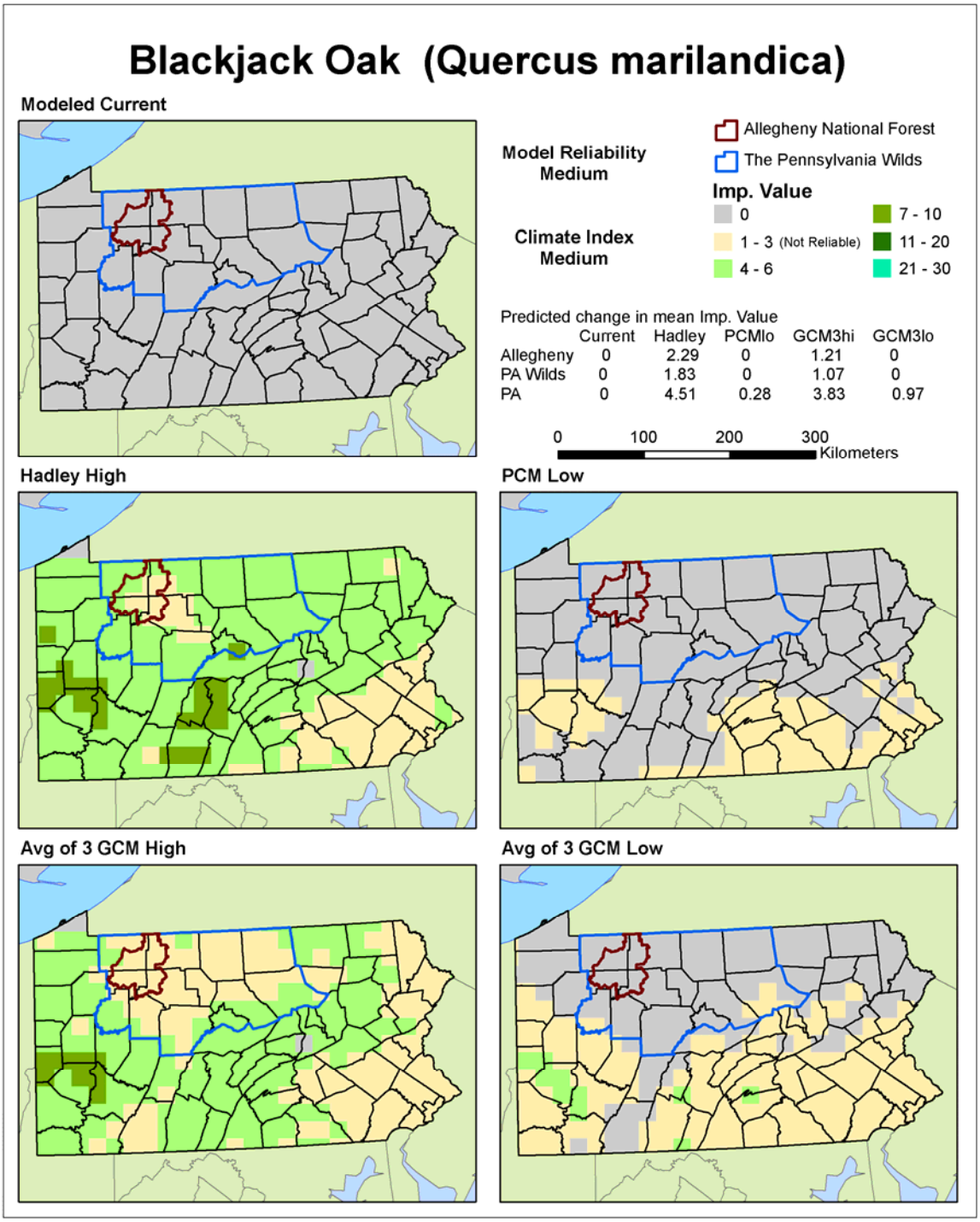

Figure A.6.28 Current modeled area-weighted habitat importance values for blackjack oak in Pennsylvania and projected 2100 importance values under four climate change scenarios.

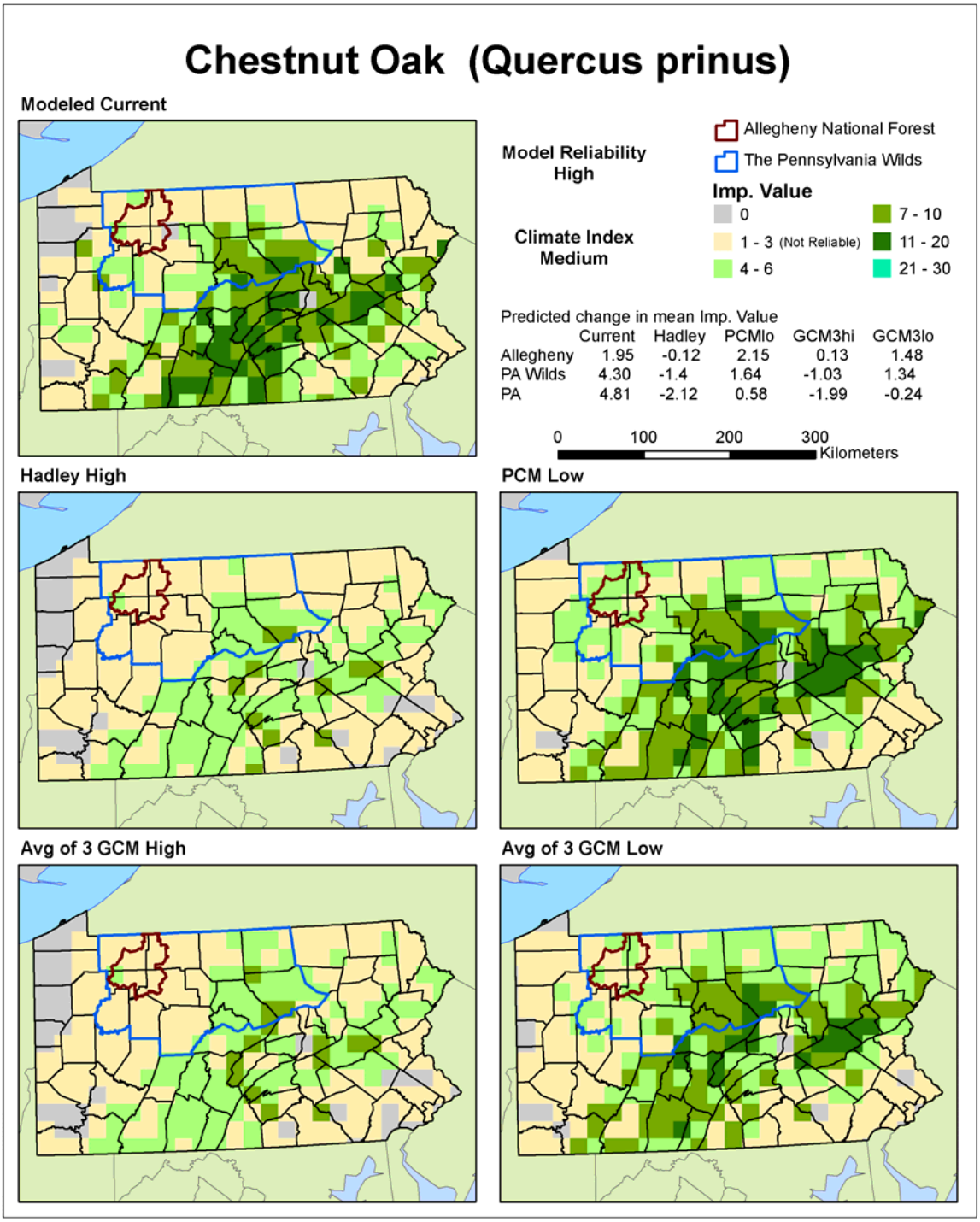

Figure A.6.29 Current modeled area-weighted habitat importance values for chestnut oak in Pennsylvania and projected 2100 importance values under four climate change scenarios.

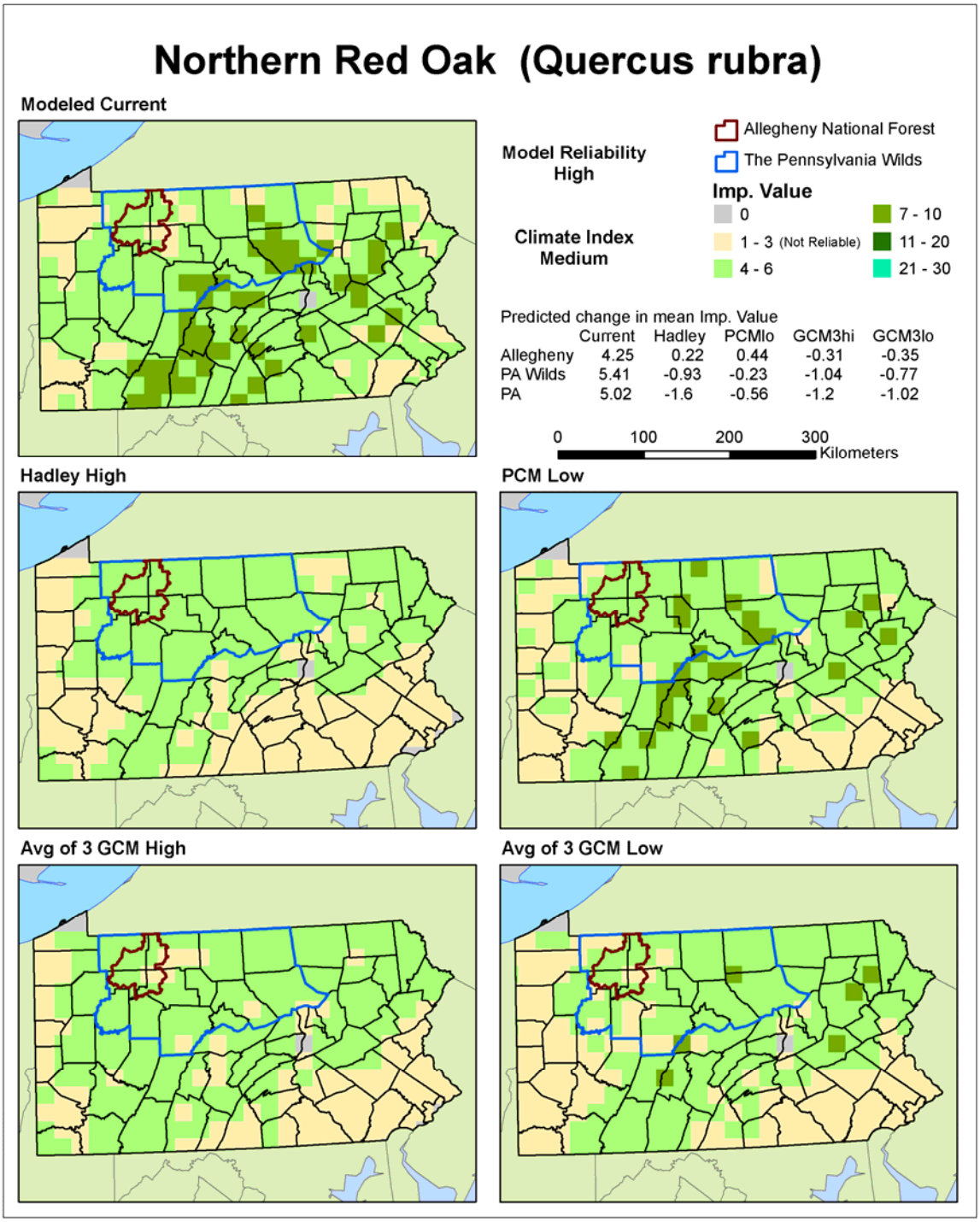

Figure A.6.30 Current modeled area-weighted habitat importance values for northern red oak in Pennsylvania and projected 2100 importance values under four climate change scenarios.

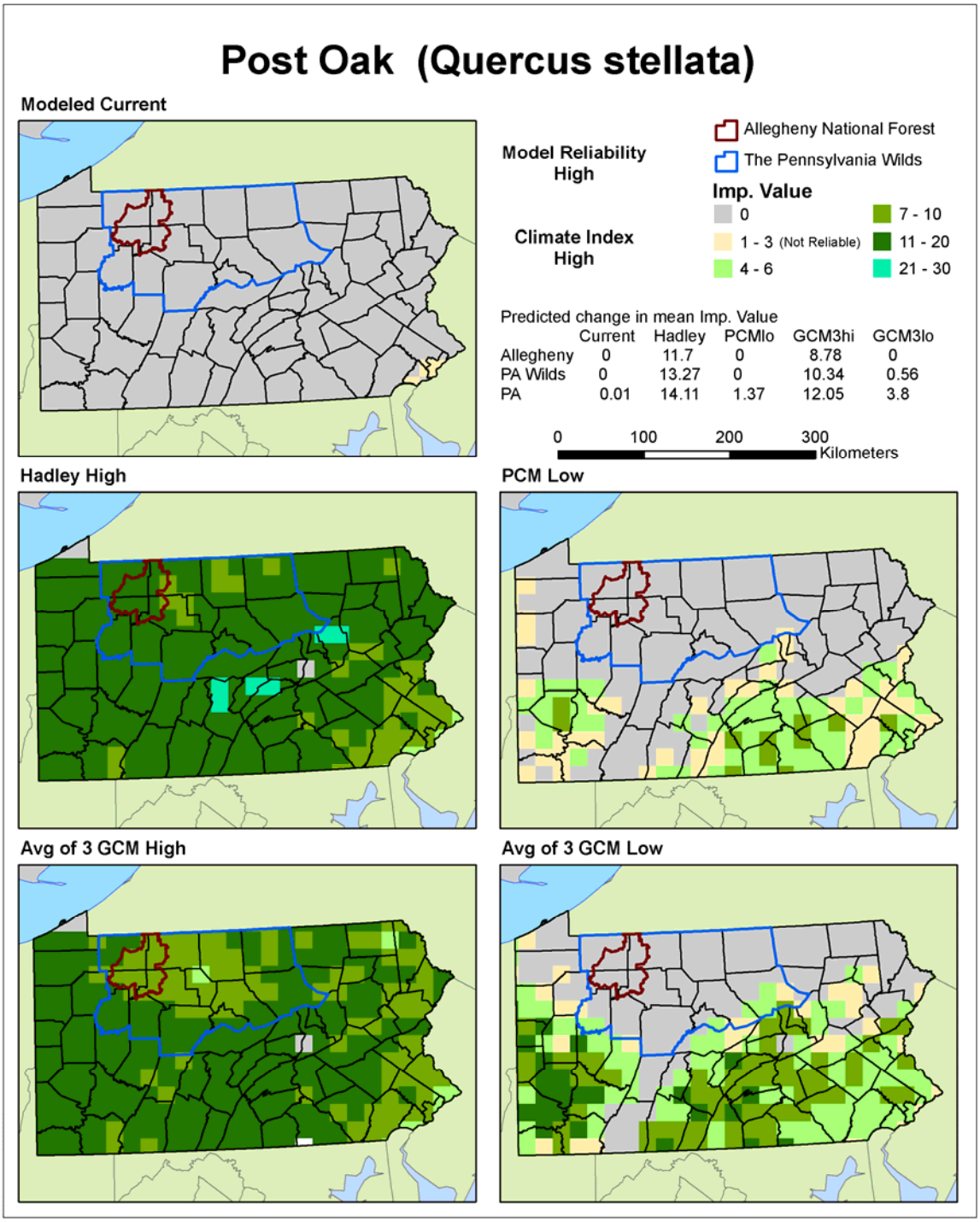

Figure A.6.31 Current modeled area-weighted habitat importance values for post oak in Pennsylvania and projected 2100 importance values under four climate change scenarios.

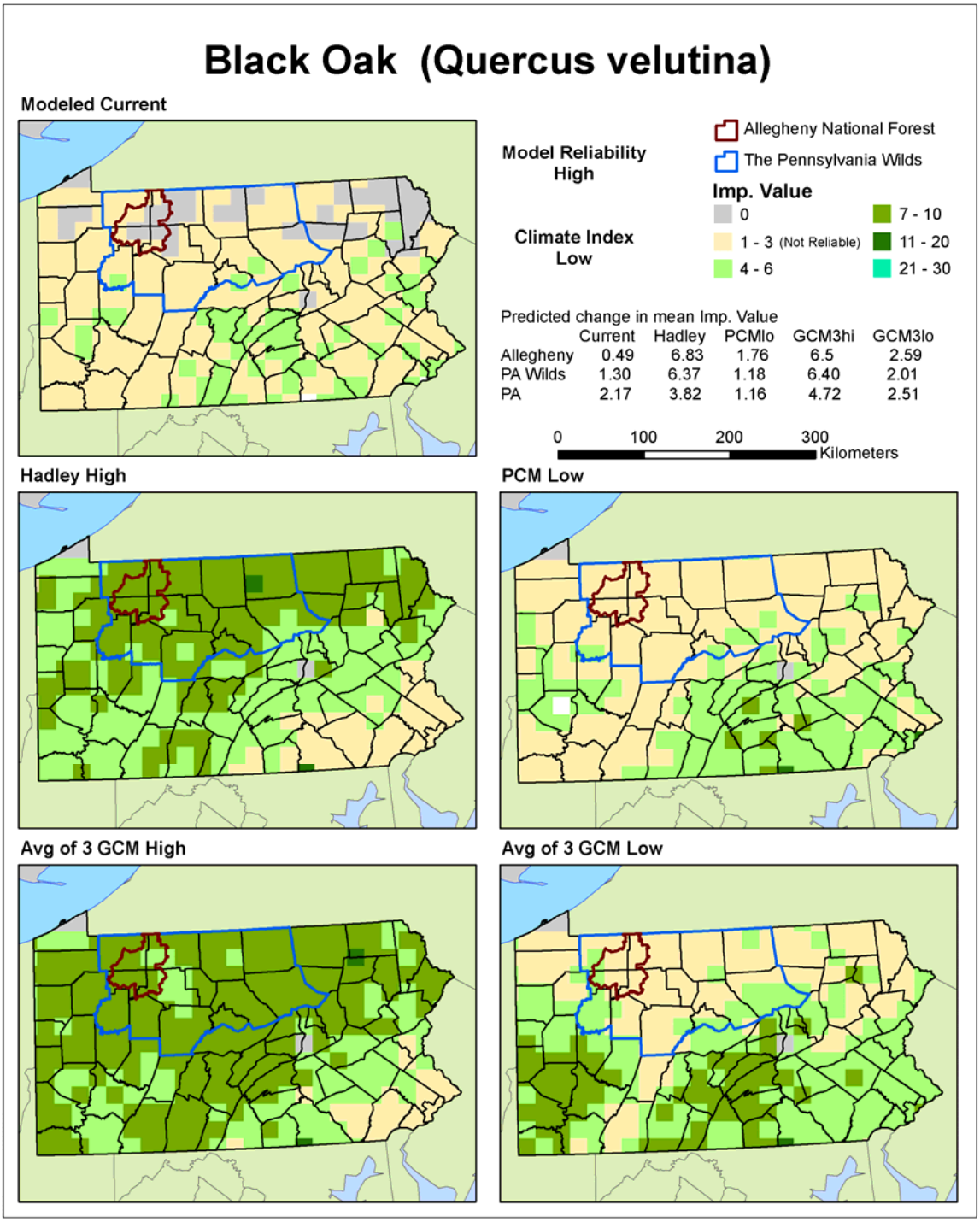

Figure A.6.32 Current modeled area-weighted habitat importance values for black oak in Pennsylvania and projected 2100 importance values under four climate change scenarios.

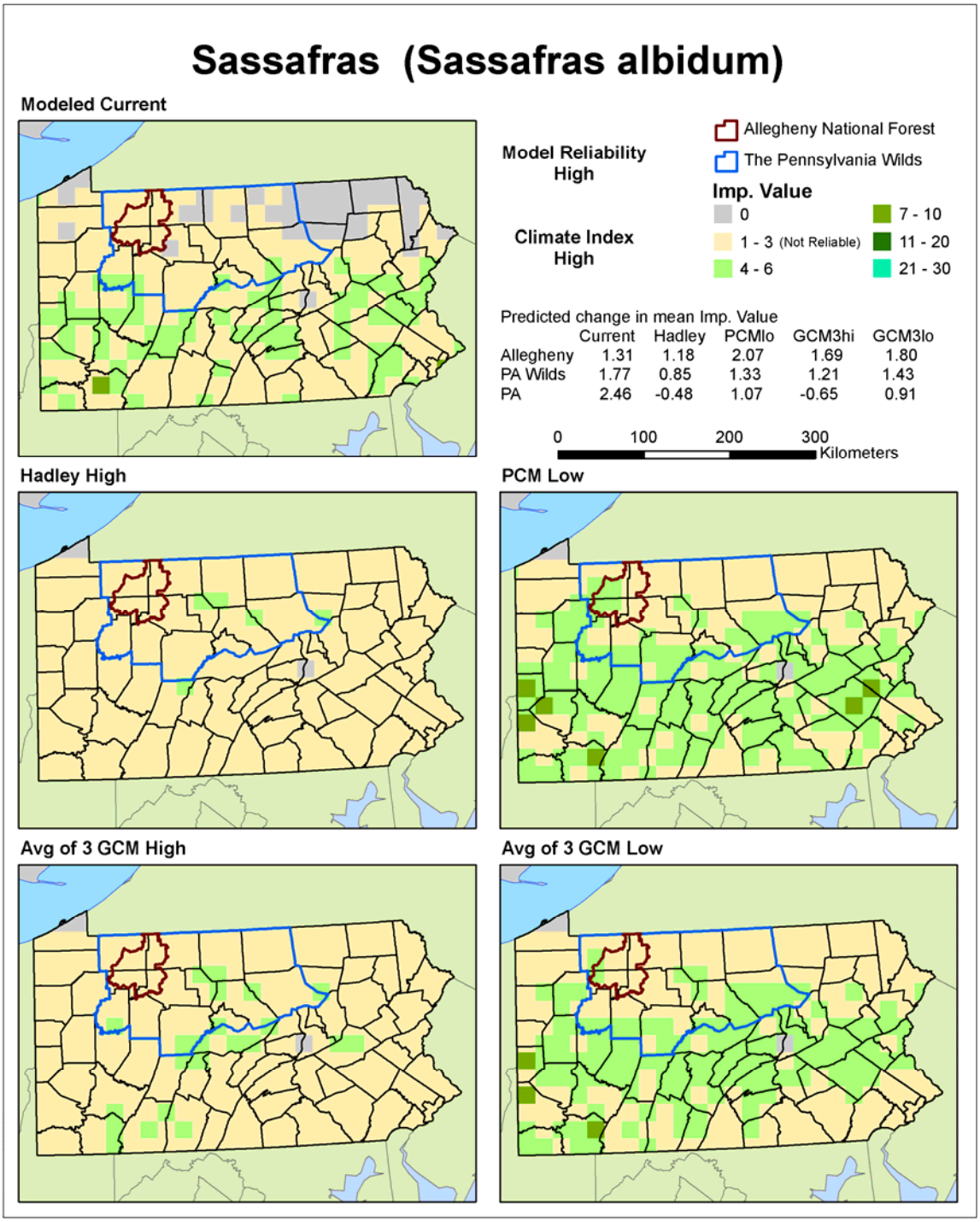

Figure A.6.33 Current modeled area-weighted habitat importance values for sassafras in Pennsylvania and projected 2100 importance values under four climate change scenarios.

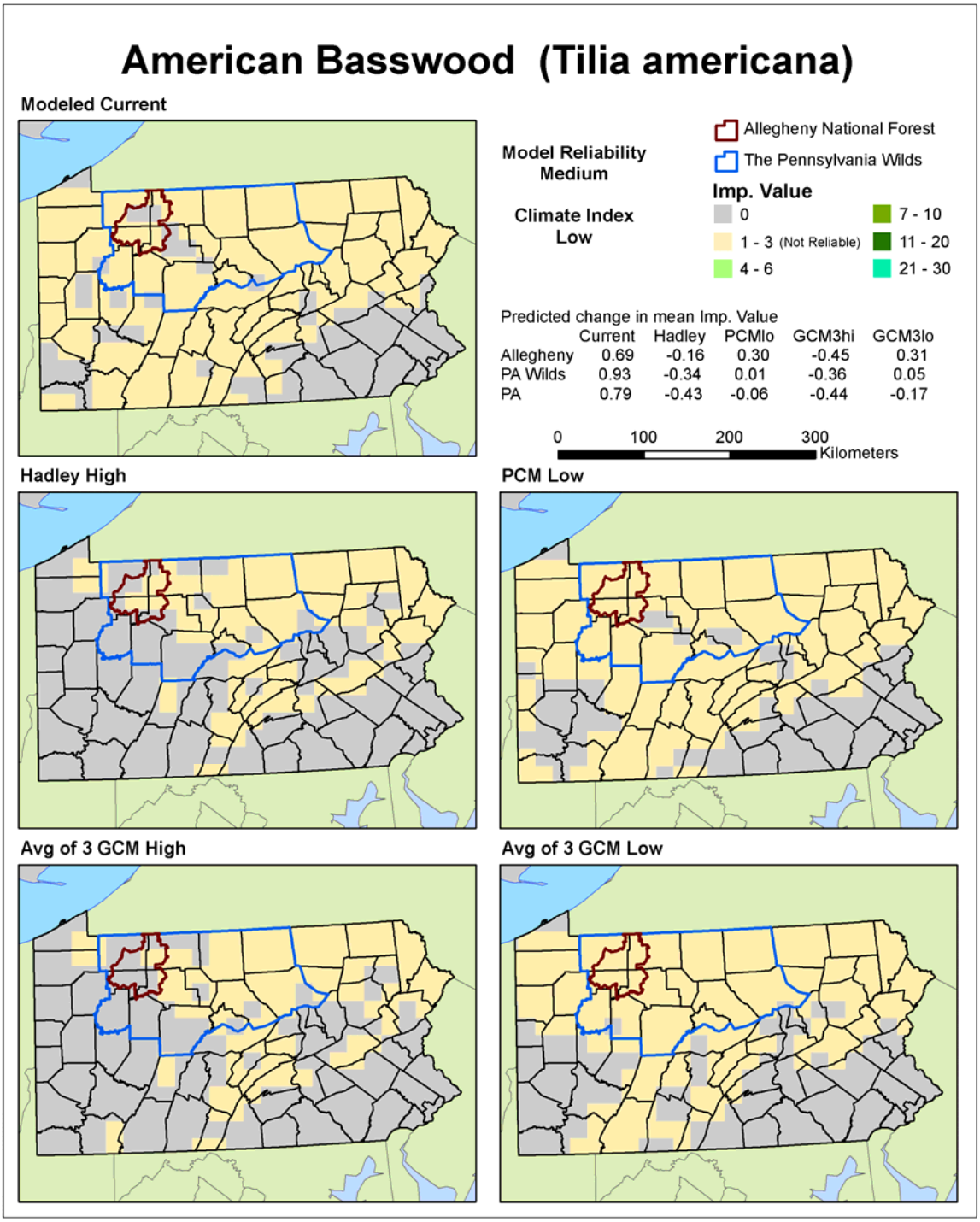

Figure A.6.34 Current modeled area-weighted habitat importance values for American basswood in Pennsylvania and projected 2100 importance values under four climate change scenarios.

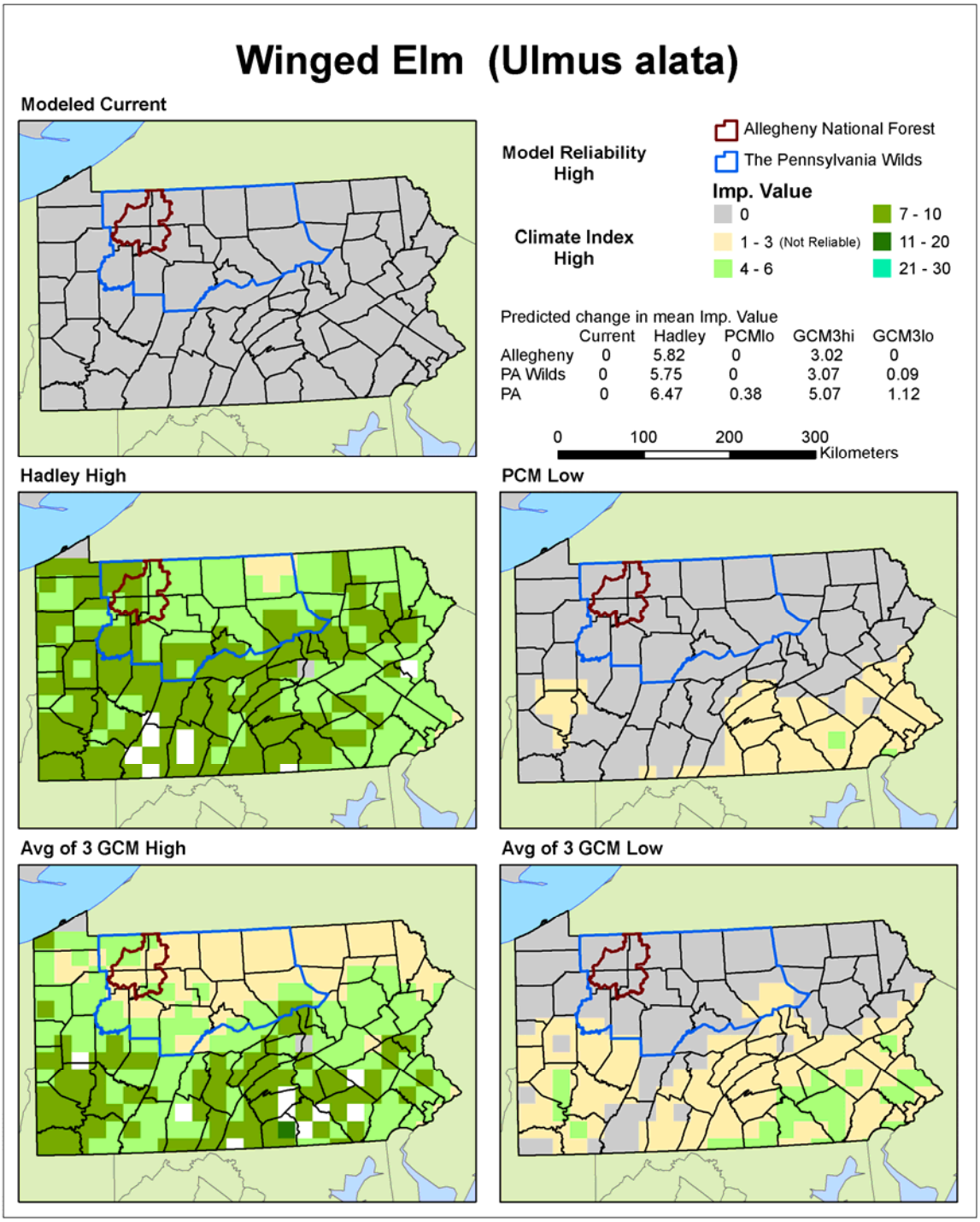

Figure A.6.35 Current modeled area-weighted habitat importance values for winged elm in Pennsylvania and projected 2100 importance values under four climate change scenarios.

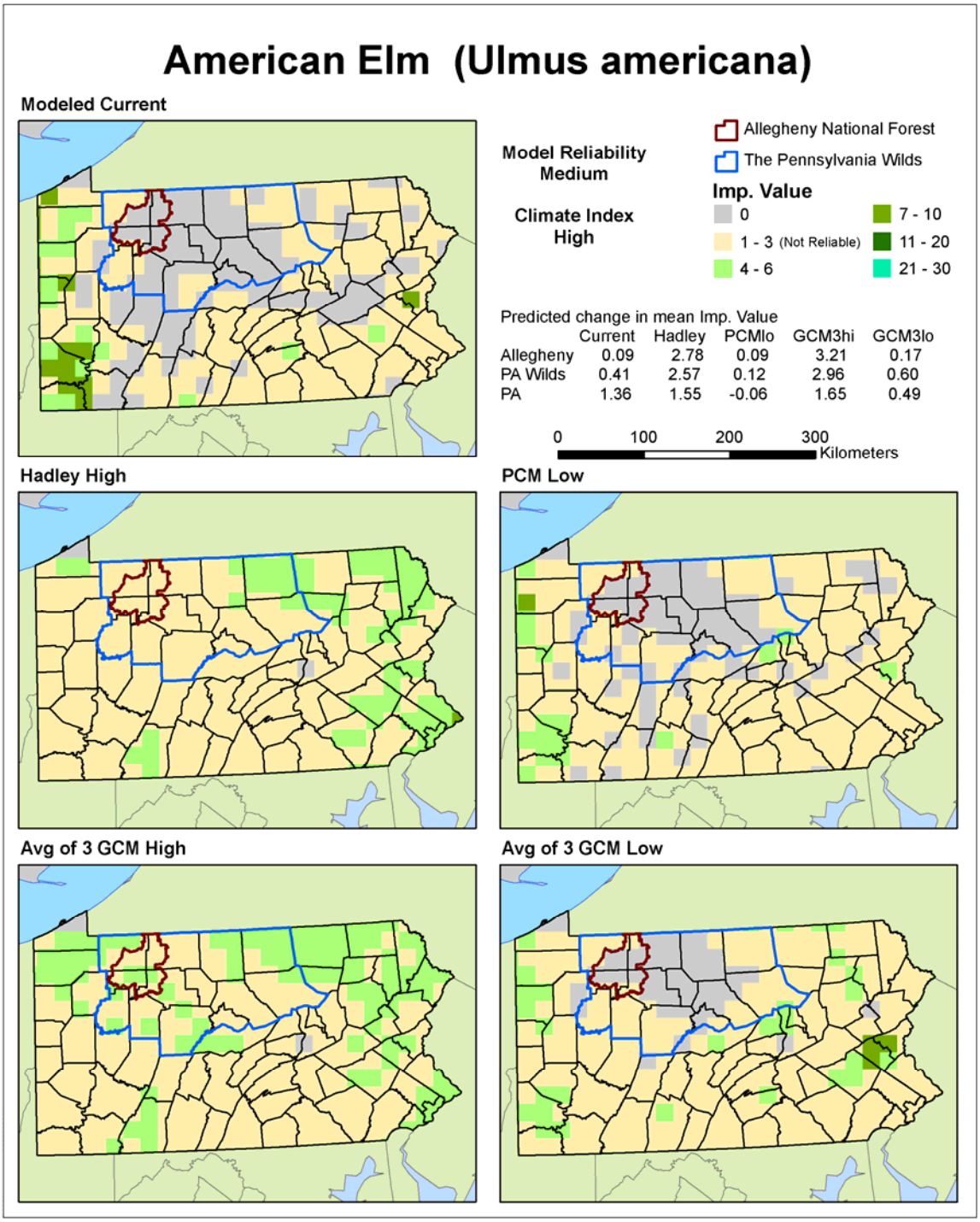

Figure A.6.36 Current modeled area-weighted habitat importance values for American elm in Pennsylvania and projected 2100 importance values under four climate change scenarios.

Appendix 7: Modeling Electricity Demand in Pennsylvania

This appendix describes the model used to estimate electricity demand growth in Pennsylvania under the climate-change scenarios described in Section 4. This model was used to generate the estimated electricity demand distributions shown in Figures 10.11(a) – (f). The model establishes statistical relationships between weather in Pennsylvania and hourly electricity demand, and uses these relationships to project the change in future electricity demand in Pennsylvania. The model only incorporates changes in electricity demand that are due to warming in Pennsylvania. The model does not incorporate the effects of future population growth, changes in the Commonwealth's economy, changes in behaviors or preferences regarding electricity use in the Commonwealth, or current (or future) policies aimed specifically at electricity demand in Pennsylvania.

Hourly statewide average temperature data for 2006 was obtained from the Web site of the Pennsylvania State Climatologist at http://pasc.met.psu.edu. Temperature data was converted into Heating Degree Days (HDD) and Cooling Degree Days (CDD), based on a reference point of 65 degrees Fahrenheit:

(1) $CDD_t = \max(0, Temp_t - 65)$

(2) $HDD_t = \max(0, 65 - Temp_t)$.

Note that equations (1) and (2) imply that for each hour t, at least one of HDD_t and CDD_t must be equal to zero. A Heating Degree Day indicates cooler temperatures and a demand for heating. A Cooling Degree Day indicates warmer temperatures and a demand for cooling.

Hourly electricity demand data for Pennsylvania utilities in 2006, in Megawatts per hour, was obtained from the Web site of PJM, LLC at www.pjm.com, and from the FERC 714 filings of individual utilities at www.ferc.gov.

The statistical relationship between temperature (HDD and CDD) and electricity demand (*ElecDemand*) was determined by estimating the following regression equation:

(3) $$ElecDemand_t = \alpha + \beta_1 \times HDD_t + \beta_2 \times HDD_t^2 + \gamma_1 \times CDD_t + \gamma_2 \times CDD_t^2 + \varepsilon_t .$$

The error term ε_t was determined to exhibit first-order serial correlation, with a coefficient of 0.97. Electricity demand generally shows a significant time trend; electricity demand during one hour is usually highly correlated with electricity demand in the previous hour.

Table A7.1 shows the estimated coefficients for Heating Degree Days and Cooling Degree Days.

Table A.7.1

Variable	Coefficient	Standard Error
Constant	82,884	1,226
HDD	-198	40
HDD^2	1.98	0.91
CDD	599	54
CDD^2	4.72	2.26

Regression R^2: 0.95
Regression S.E.: 3,264

The GCM outputs for seasonal warming for Pennsylvania under two climate scenarios (A2 and B1, as outlined in Section 4) were used to construct estimated hourly Heating Degree Days and Cooling Degree Days for three 20-year time periods: 2011 – 2030; 2046 – 2065; and 2080 – 2099. The analysis in Chapter 10 used the maximum, minimum and median amount of warming to create a range for each of the 20-year time periods. The estimated Heating Degree Days and Cooling Degree days during hour *t* in season *s*, during the 20-year time period *k* are given by:

(4) $$HDD_{t,s,k} = \max\left[0, 65 - (Temp_t + \Delta Temp_{s,k})\right]$$

(5) $$CDD_{t,s,k} = \max\left[0, (Temp_t + \Delta Temp_{s,k}) - 65\right],$$

where $\Delta Temp_{s,k}$ is the amount of warming (in degrees Fahrenheit) during season *s* in time period *k*, as determined by the GCM output.

Finally, the coefficient estimates from equation (3) were used to estimate hourly electricity demand, given the amount of warming predicted by the GCM:

(6) $$ElecDemand_{t,s,k} = 82,884 - 198 \times HDD_{t,s,k} + 1.98 \times HDD^2_{t,s,k} + 599 \times CDD_{t,s,k} + 4.72 \times CDD^2_{t,s,k} + \varepsilon_t.$$

Equation (6) was estimated for the maximum, minimum and median values of $HDD_{t,s,k}$ and $CDD_{t,s,k}$ to obtain the ranges of electricity demand for each climate scenario and each time period.

Appendix 8: Public Comment and Response Document

PENNSYLVANIA
CLIMATE IMPACT ASSESSMENT REPORT

COMMENT AND RESPONSE DOCUMENT

June 11, 2009

INTRODUCTION

The Draft Pennsylvania Climate Impact Assessment Report (Draft Report) was prepared under contract by The Pennsylvania State University for the Department of Environmental Protection to meet the requirement in Act 70 of 2008 (Act 70). Act 70 specifically requires that the report identify the following information:

(1) Scientific predictions regarding changes in temperature and precipitation patterns and amounts in this Commonwealth that could result from climate change. Such predictions shall reflect the diversity of views within the scientific community.
(2) The potential impact of climate change on human health, the economy and the management of economic risk, forests, wildlife, fisheries, recreation, agriculture, tourism and any other aspect of this Commonwealth, and any significant uncertainties about the impact of climate change.
(3) Economic opportunities for this Commonwealth created by the potential need for alternative sources of energy, climate-related technologies, services and strategies; carbon sequestration technologies; capture and utilization of fugitive greenhouse gas emissions from any source and other mitigation strategies.
(4) Barriers to exploiting the opportunities identified in Section II Subsection (3) should also be identified.

Potential pathways for developing the impacts assessment report were first discussed with the Climate Change Advisory Committee (CCAC) at the September 5, 2008 meeting. A first draft of a solicitation for the work to be performed was reviewed with the CCAC during the October 21, 2008 conference call meeting. A subsequent decision was made by DEP based on recommendation by CCAC to seek out and contract the services of an academic team of researchers from within Pennsylvania. On December 8, 2008 a webinar was provided to the committee identifying the candidate members of the research team and to explain the proposed methodology for performing the assessment. A final contract with the Pennsylvania State University was issued on March 2, 2009. The Draft Report was distributed to the CCAC and made available to the public on the department's internet website on April 15, 2009. A 30-day public comment period commenced with all comments required to be delivered to DEP on May 18, 2009. The Draft Report was reviewed and discussed with the CCAC during meetings on March 27, 2009 and April 30, 2009. Further discussion occurred during the May 26, 2009 meeting.

In assembling this document, the department has addressed public comments associated with the Draft Report. For the purposes of this document, comments of similar subject material have been grouped together and responded to accordingly. During the public comment period, the department received approximately 27 public comments from 6 organizations. The following table lists these organizations. The Commentator ID number is found in parentheses following the comments in the comment and response document.

List of Commentators

Commentator ID Number	Name	Address
1	Raymond L. Reaves	Pittsburgh, PA
2	Dr. Melanie Fitzpatrick Climate Impacts Scientist Union of Concerned Scientists	Cambridge, MA
3	Dr. Louis R. Iverson Research Ecologist USDA Forest Service	Delaware, OH
4	George Ellis President PA Coal Association	Harrisburg, PA
5	Mr. David C. Cannon Jr. VP, Environment, Health & Safety Allegheny Energy	Greensburg, PA
6	Ms. Stephanie Catarino Wissman Director, Government Affairs PA Chamber of Business and Industry Accompanied by comments from Dr. Margo Thorning American Council for Capital Formation	Harrisburg, PA

COMMENTS AND RESPONSES

1. The report is well researched and the recommendations for action appear reasonable. The need for action is commanding. (1)
   Response: *The department acknowledges the comment.*

2. The report authors should be congratulated on their thorough presentation and the exhaustive reference list. The assessment captures the important sectors that are most relevant to the economic, social and ecological health of the state. (2)
   Response: *The department is pleased with the quality of work represented in the report. The report incorporates those sectors that have been identified as requirements of Act 70.*

3. There is a need for balance between available information and expert assessment; more targeted research is needed at the state and local level. (2)
   Response: *The department acknowledges that targeted research is always helpful. The department believes this report satisfies the requirements of Act 70; furthermore the Department is going beyond Act 70 in commissioning a separate macroeconomic*

impact assessment that is specific for Pennsylvania. The detailed analysis is expected at the end of the calendar year.

4. The report could point out the need and mechanisms for cross-agency interaction. (2)
   Response: *As required in Act 70, state and federal agencies contributed to the development of the final report. Acknowledgement of the agencies' contributions is provided in the report on page 4. The intent of the report is to inform the decision-making process.*

5. A section is needed to collate management strategies for early adaptation measures. (2)
   Response: *Adaptation strategies are addressed in various chapters, including Chapter 14, Economic Barriers and Opportunities, which has been extensively revised in the final report. The scope of this report was not intended to discuss management strategies.*

6. It would be useful to point out in the Executive Summary that lower [emissions] scenario futures give quantifiable benefits for water resources, human health impacts and agriculture. (2)
   Response: *The report examines both higher and lower emission scenarios with positive and negative impacts. Quantifiable impacts are provided for multiple scenarios. The information is found in the various chapters of the report.*

7. A conclusion chapter is suggested to summarize the opportunities and barriers. (2)
   Response: *The final report includes Chapter 14, Economic Barriers and Opportunities, which addresses this issue.*

8. The report is accurate and thorough as it pertains to forests of the Allegheny Plateau and potential changes in species habitat. (3)
   Response: *The department acknowledges the comment.*

9. The report glosses over potential impacts that strategies to reduce carbon emissions may have on the economy and electric rates (4).
   Response: *A more robust discussion of the benefits and impacts is warranted. As a result, the department has gone beyond the requirements of Act 70 to commission a macroeconomic study to identify these and other issues. This study will be completed following the development of a computational general equilibrium (CGE) model. The resultant analyses from the CGE model are expected at the end of the calendar year.*

10. There are conflicting statements and lack of detailed analysis on certain impacts. For example, obvious pathways for GHG reductions are discussed on page 181 which offers two key strategies – a carbon tax and demand side response (conservation and efficiency). Two pages later, the report cites study performed by Newcomer, et al., which concludes that the only real scenario to limit emissions is through energy efficiencies. (4)

Response: *Act 70 requires discussion of diversity of views from the scientific community. The Newcomer study is indicative of that author's perspective.*

11. There is lack of documentation. For example, on page 188, the report states "studies" show that people are willing to bear higher energy costs, but there are no references for those studies. (4)
    Response: *The report contains extensive references and citations and follows established guidelines for scientific publication. The authors have reviewed the report to be sure the documentation is complete. The referenced discussion on page 188 is adequately cited as Palmgren, et al., 2004.*

12. The report does not meet the legislative intent of Act 70. (4, 5, 6)
    Response: *The department strongly disagrees. Act 70 is very specific as to the content of the impacts assessment report. The report and the solicitation to develop this report are reflective of those requirements. The department believes the final report is inclusive of public input, as represented by this comment and response document, and fulfills the statutory obligations of Act 70 of 2008. The department has gone beyond the requirements of Act 70 to provide additional information to the General Assembly. A detailed macroeconomic study will be completed following the development of a computational general equilibrium (CGE) model. The resultant analyses from the CGE model are expected at the end of the calendar year.*

13. The report fails to reflect the view of the Climate Change Advisory Committee. (4, 6)
    Response: The department disagrees. *The committee was extensively consulted in the drafting of the solicitation for this report and was further briefed about the research team and the methodology for preparing this report. The committee was also provided with opportunities to comment on the report, in a process separate from the public comment period.*

14. The report does not adequately address the diversity of views within the scientific community, as required by Act 70 of 2008. The report accepts the findings and conclusions of the Fourth Assessment Report of the IPCC. Implicit in the PA report's message is that the science is settled on this subject and that there is no scientific dissent. The reader is left with the misunderstanding that there is consensus within the scientific community on this point. A chorus of skeptical scientific viewpoints continues to be voiced about the science of climate change. (4, 5, 6)
    Response: *Contrarian viewpoints are recognized in the report, but the overwhelming view of climate scientists is that anthropogenic climate change is real and significant. For this reason, the two opposing points of view should not be given equal weight. In broad agreement with the IPCC report and its main findings are statements and reports from 11 of the world's national science academies[16], Synthesis and Assessment Products of the U. S. Climate Change Science Program[17], and the following scientific societies: The American Meteorological Society[18], The American*

[16] http://nationalacademies.org/onpi/06072005.pdf
[17] http://www.climatescience.gov/
[18] http://www.ametsoc.org/policy/2007climatechange.html

Geophysical Union[19], The Geological Society of America[20], The European Geosciences Union[21], The American Chemical Society[22], and The American Association for the Advancement of Science[23]. Surveys of climate scientists, particularly those that are actively publishing, also indicate overwhelming support for the view that anthropogenic climate change is real and significant[24]. Much of the contrarian viewpoint (such as what is expressed in the 2009 Minority Report of the U.S. Senate and Public Works Committee and the NY Times article about Freeman Dyson) emerges in outlets that are not subject to peer review, such as the public media and the internet. It is not feasible nor is it appropriate for every possible viewpoint to be recognized; the report has emphasized the peer-reviewed literature as its main source of information. Though some peer-reviewed literature questions the IPCC conclusion that anthropogenic climate change is real and significant, a comparable body of literature suggests that the IPCC has underestimated human-induced climate change and its impacts. The report has been amended to include a section (4.3) on the causes of recent climate change, which addresses a number of these issues.

15. The report fails to acknowledge the view that negative feedbacks (cooling mechanisms), particularly those of clouds, have been underestimated or are poorly understood. (6)
    Response: *The department disagrees. Section 4.1 of the report discusses climate feedback mechanisms, including those of clouds. For example, this section states that "One of the most important of these [feedback mechanisms] involves changing cloud cover." The section also states that "The feedback process in this case is much more complicated than with snow and ice cover because clouds both reflect solar radiation (so they cool the system) and at the same time absorb longwave radiation (so they enhance the greenhouse effect and warm the system). Which feedback dominates depends on (amongst other things) the altitude of the cloud and its geographic location …" The report also acknowledges uncertainty in feedback mechanisms: " … as we move toward a warmer world, there may be other positive or negative feedback processes that are either not included or not well simulated in the present models." Further, the report includes a diversity of model projections in Chapters 4 and 5 and attributes the range to the uncertainty in feedback mechanisms. For example, Chapter 4 states that "[the models] differ in the way they treat some of the more important feedback processes. Differences in the way they treat clouds, for example, accounts for a significant proportion of the models' sensitivity to change." Therefore, by using a diversity of models, the report embraces the uncertainty in feedback processes, both positive and negative, to the extent that it is possible.*

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[19] http://www.agu.org/sci_soc/policy/positions/climate_change2008.shtml
[20] http://www.geosociety.org/positions/position10.htm
[21] http://www.egu.eu/fileadmin/files/egustatement.pdf
[22] http://portal.acs.org/portal/fileFetch/C/WPCP_011538/pdf/WPCP_011538.pdf
[23] http://www.aaas.org/news/press_room/climate_change/mtg_200702/aaas_climate_statement.pdf
[24] Doran, P. T. and M. Kendall Zimmerman (2009) Examining the scientific consensus of climate change, *EOS, Transactions of the American Geophysical Union, 90,* 22-23.

16. The report omits diverse scientific views in the scientific community regarding the Pacific Decadal Oscillation (PDO) as, potentially, the primary driver for climate change. (6)
    Response: *The report discusses natural climate variability in Section 4.1, though does not specifically address the PDO. The authors of the report are open to reviewing references to peer-reviewed publications that suggest a dominant role of the PDO in global warming over the past 100 years.*

17. The scientific community has recently engaged in a vigorous debate regarding the probability of increased storms and hurricanes, or lack thereof, but little mention of this appears in the report. (6)
    Response: *The department disagrees. Section 5.2.4.2 discusses in detail a number of studies, including several that were published after the 2007 IPCC report, of future projections of the intensity and frequency of tropical storms and extra-tropical winter cyclones. If there are additional studies that should be cited, the authors of the report are open to reviewing the references.*

18. The report ignores the recent data that suggest that global average temperatures have not increased in recent years, and that cooling may actually be occurring. (6)
    Response: *The report has been revised to include Section 4.3 that addresses the causes of recent climate change, including the weak global temperature trend since 1998.*

19. The report does not adequately provide alternative views as to the potential negative impacts that may be realized by certain industries if mandatory GHG reductions or a carbon tax were imposed nor does it provide adequate discussion of the challenges associated with implementing possible mitigation strategies such as increasing levels of renewable energy and fuels. (6)
    Response: *A thorough analysis of how industry could be impacted from the possible enactment of a federally mandated cap on greenhouse gas emissions and/or a carbon tax is beyond the scope of this report and the requirements of Act 70.*

20. The draft impacts assessment report relies almost exclusively on the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC). (4, 6)
    Response: *The department disagrees. The IPCC report is one source of information and a number of other sources were used as well. The fairly exhaustive literature research from the authors went well beyond the IPCC report. The models used in the Pennsylvania report are generally the same models used in the IPCC report. These models represent the majority of global climate models that are in existence. The specific models used in this report have been published in the peer-reviewed literature, have been run for a consistent suite of future emissions scenarios, and for which output is readily available. The models were not developed specifically for the IPCC. Some models have a heritage that dates back to the 1960s, such as the GFDL models, which were developed in U.S. government laboratories. The report's use of the models specifically for Pennsylvania is unique. The report carefully evaluates the*

models extensively for Pennsylvania before using them for future projections. In Section 5.4, the performance of the models was examined to see how well the model average had performed in the 20th century. Using this back casting method, the models were accurate in their predictions.

21. Provide greater or more detailed economic analyses for each section or for the full report (5).
    Response: *The authors have revised Chapter 14, Economic Barriers and Opportunities. The report meets the requirements of Act 70. In addition, the department has gone above and beyond the requirements of Act 70 to commission a macroeconomic study to identify these and other issues. This study will be completed following the development of a computational general equilibrium (CGE) model. The resultant analyses from the CGE model are expected at the end of the calendar year.*

22. The time and resources provided were inadequate (5).
    Response: T*he department has strived to provide the best possible product while adhering, as closely as possible to the statutory timeline of Act 70 while also recognizing the opportunity afforded by the Act to update this work on a consistent and subsequent basis.*

23. The report lacks consistency in qualifying the relative certainty/uncertainty being described within the various sections and calls into question the objectivity of the authors (6).
    Response: *The report has been reviewed and revised as necessary to reflect the relative certainty and uncertainty being described in the various sections. For example, the first paragraph of the Executive Summary and the second paragraph of the Introduction have been revised to reflect the uncertainty. Revisions were made throughout the report in response to comments about uncertainty, specifically in Chapters 4, 5, 9, 11 and 12.*

24. Given the lack of Pennsylvania specific data, qualifying statements in the report need to be dealt with a more consistent manner (6).
    Response: *The authors used Pennsylvania data where available and other studies which are applicable for Pennsylvania's location in the northeastern United States. The department does not believe that new research is necessary for Pennsylvania to broadly understand how the climate within Pennsylvania is likely to change in the coming decades.*

25. The Executive Summary should include greater qualification and discussion that could assist policy makers in reaching a conclusion to support or not support very specific policy measures that may be considered with regard to climate change mitigation. Specifically, the report should discuss the social and economic impacts of less coal production and/or utilization if a carbon price is established and as this price may increase and also discuss the impacts of "decarbonization" (6).
    Response: *To facilitate this type of discussion, the department has gone beyond the requirements of Act 70 to commission a macroeconomic study to identify these and*

other issues. This study will be completed following the development of a computational general equilibrium (CGE) model. The resultant analyses from the CGE model are expected at the end of the calendar year. The impacts assessment's treatment of mitigation measures is limited to identifying economic barriers and opportunities.

26. The report does include chapters dedicated to "Land Use and Transportation or Residential and Commercial." (6).
    Response: *In this respect Act 70 is very specific as to the content of the impacts assessment report. The report and the solicitation to develop this report are reflective of those requirements. Act 70 requires the department to prepare impact assessment reports every three years and the department will take this recommendation into consideration for subsequent reports.*

27. The report addresses the need for adaptation strategy but the DEP has been reluctant to take up discussion of this topic (6).
    Response: *The department's primary responsibility is addressing the requirements of Act 70. As per Act 70, adaptation is beyond the scope of this report. The Climate Change Advisory Committee discussed this topic and the department has suggested addressing adaptation strategy after completion of the action plan at future Climate Change Advisory Committee meetings.*

28. The report should acknowledge the models' limitations given all of the variables associated with human activity/behavior and with natural climate variability associated with the Pacific Decadal Oscillation, solar activity, and a host of more transient climate conditions. (6)
    Response: *The report has been revised to include a new Section 4.3 on the causes of recent climate change. The report acknowledges these limitations and the department believes that no further qualification is necessary.*

29. Using the mean of divergent climate models is not the best approach to rationalize the difference expressed by these models (6).
    Response: *The department believes this is an acceptable approach in climate modeling and notes that the report has not limited presentation of data to only the mean of these models. The multi-model mean is shown in the report to produce the best simulation of Pennsylvania's climate. The mean of precipitation and temperature numbers from the suite of General Circulation Models were tested for accuracy using back casting. The output of the models is expressed as a range of possible outcomes. The standard deviation is used in model evaluation and data have been presented to show quartile distributions that reflect the full range of model projections.*

Appendix 9: Agency Comment and Response Document

PENNSYLVANIA
CLIMATE IMPACT ASSESSMENT REPORT

PENNSYLVANIA AGENCY COMMENTS

DEPARTMENT OF COMMUNITY AND ECONOMIC DEVELOPMENT

There are two primary topics that have dominated the national debate on climate change, and not adequately addressed by the Draft Report. These topics directly impact Pennsylvania businesses and may help inform future legislative action.

The imposition of Carbon Tax verses Cap and Trade: Upon passage of climate legislation, businesses will be motivated to reduce their carbon footprint in advance of the cap-and-trade system to be launched in 2012 by the Federal government. The report should explore the comparative merits of each option and highlight how the proposed federal act may impact Pennsylvania's economy.
Response: *A thorough analysis of how industry could be impacted from the possible enactment of a federally mandated cap on greenhouse gas emissions and/or a carbon tax is beyond the scope of this report and the requirements of Act 70. This report is limited to identifying the impacts that unmitigated climate change could have on Pennsylvania. The department supports discussion at future Climate Change Advisory Committee meetings.*

Innovation and Climate Change: Climate legislation could also help restore innovation. For example, no company would want to make high-risk investments to develop or deploy complex new energy systems when the results of the costly learning-by-doing may not be beneficial. There is also need to increase clean-energy R&D while also offering subsidy support to bring technologies to cost-effective scale for categories such as solar photovoltaic power and geothermal energy. These topics should be explored with an emphasis on the impact to businesses in the Commonwealth.
Response: *A more robust discussion of innovative technologies and impacts is warranted. The department has commissioned a macroeconomic study to identify these and other issues. This study will be completed following the development of a computational general equilibrium (CGE) model. The resultant analyses from the CGE model are expected at the end of the calendar year. The department supports discussion at future Climate Change Advisory Committee meetings.*

DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

Overall, the report maintains an objective review of the information that is currently known on the potential impacts of climate change, relating to four specific modeled outcomes, and general overviews of suggested potentials or probabilities.
Response: *The department acknowledges the comment.*

INSURANCE DEPARTMENT

The research team did a very thorough and professional job and came to a fair conclusion. For next steps, we would recommend that you discuss climate change and its impact on the health or life insurance industry. Natural catastrophes kill thousands of people and disease and famine kill millions. You may want to include some research/discussion on these two insurance segments down the road.
Response: *The department acknowledges the comment and supports discussion at future Climate Change Advisory Committee meetings.*

PA DEPARTMENT OF AGRICULTURE

With regard to the discussion on an increasing population in the southeast (PA) and sprawling land use patterns that continue the conversion of agricultural lands, PDA has offered that the Pennsylvania's Farmland Preservation program has preserved over 400,000 acres of farmland to date, preserving the land solely for agricultural use.
Response: *The report was revised in Section 9.2.1 based on the comment.*

PDA maintains a commitment to cellulosic ethanol being the primary agricultural source of feedstock for fuel. We are a corn deficient state (a net importer of corn), and corn production for biofuels would not be feasible or favorable for the livestock industry in the Commonwealth.
Response: *The report was revised in Section 9.3.3 based on the comment.*

Farmers are already engaged in many of the identified mitigation practices and opportunities. Farmers are investing in on-farm energy conservation and production measures. With regard to the suggestion that a cap and trade or carbon tax may hasten development or deployment of these opportunities, PDA does not believe that a cap and trade or carbon tax is essential to realizing these benefits.
Response: *The department agrees. The report was revised to address these comments in Section 9.5.*

With regard to research needs, PDA has a fairly extensive list of research priorities is endorses along with the Chesapeake Bay Biofuels strategy. Perhaps the language of those priorities should be adopted in this document.
Response: *The department acknowledges the comment. It is not within the scope of this report to address research priorities.*

PA DEPARTMENT OF TRANSPORTATION

The ramifications of global warming on the transportation sector are wide and varied. Climate change will affect every type of transportation through rising sea levels, increased rainfall, surges from more intense storms, and heat related events. These impacts include, but are not limited to, some of the following:

* The rise in sea level could have possible flooding impacts on seaboard highway/roads that are currently at or slightly above sea level at this time. The I-95 corridor in the Philadelphia area is a prime example.
* More frequent rain events in early and late winter, verses snow events, lead to small stream flooding which in turn increase flooding on many state and local roads
* Repairs associated with heat buckling of highways
* Road subsidence from melting permafrost
* Required road weight limits due to overheated pavements
* Extreme thermal expansion of bridge joints
* Greater flooding events could cause eroding of bridge foundation supports
* Heat induced rail track deformation
* Flooding of tunnels
* Increased airport delays (weather related) or flooding of runways
* Need for harbor and port improvements due to higher tide
* Flooded railway beds, sedimentary shifts/mudslides onto tracks or the undermining of railway beds
* Flooded ports-of-call

Given the vast transportation system and the significant impacts to mobility in the Commonwealth due to future impacts of climate change, we at the Department of Transportation believe that future studies should include transportation.

Response: *The department appreciates the level of detail provided in this comment. Act 70 is very specific as to the content of this impacts assessment report; the solicitation to develop this report was reflective of the Act's requirements. Further, Act 70 requires the department to prepare impact assessment reports every three years and the department will take this recommendation into consideration for subsequent reports.*

PA FISH AND BOAT COMMISSION

Note: *All suggested specific revisions from PFBC were implemented. A substantial paragraph was added re: eastern brook trout impacts, and brook trout considerations were added to the impacts summary, adaptations, and necessary information sections.*

Page 115: Paragraph 1 and 2 list two different totals for miles of streams in PA. Paragraph 1 says that there are over 86,000 miles of streams while paragraph 2 states that there area 83,184.
Response: *The report was revised in Section 8.0 based on the comment.*

Page 116: The first paragraph in Chapter 8 (Page 115) states "For example, the trout population of a headwater stream is dependent upon wetland habitat along its edge. For that reason, we discuss the impacts of climate change on wetlands and headwater streams as a riparian ecosystem, and as representative of the majority of the aquatic ecosystems in the commonwealth." Then the first full sentence on page 116 states that "upstream freshwater reaches provide critical spawning and nursery habitats for migratory fish species such as alewife, Atlantic sturgeon, and the federally endangered short-nose

sturgeon." This could lead the reader to believe that alewife, Atlantic sturgeon, and the federally endangered short-nose sturgeon spawn in these very headwater streams. That is not the case.
Response: *The report was revised as suggested to clarify the spawning of migratory fish in Section 8.1.*

Pages 119/120 and 121: The last sentence on page 119, which continues onto page 120. This sentence is likely counterintuitive to many readers. I would think that increased flushing of sediments and contaminants would be a good thing. I would suggest expanding upon this as to why this would result in declined water quality. Additionally, the first full sentence on page 121 indicates that larger peak flows will result in higher rates of sedimentation and increased scouring . . . This is counter to the sentence on pages 119 and 120 where you indicate that more intense storm flows will result in increased flushing of sediments not higher rates of sediment.
Response: *The report was revised as suggested in Section 8.3.*

Page 120: Second to last sentence. "In addition, the more r-selected traits. . . ." Need to define r-selected traits.
Response: *The report was revised as suggested in Section 8.3.*

Page 221: PA resident participation in water-based recreation (page 221) is calculated through the National Survey of Recreation and the Environment. PFBC was surprised with the results. For example, PA is the 12th ranked state for boat registrations and motor boating is listed at 6% less than the national average. Estimates for PA resident participation in un-powered boats (canoeing, sailing, rowing and kayaking) seem significantly lower than expected but the PFBC has no empirical data to the contrary.
Response: *The NSRE is the only available national survey, and its results are not necessarily inconsistent with the evidence provided by the commenter. While Pennsylvania does rank high in boat registrations, the number of boat registrations per 1000 residents is 29, compared to 46 nationally (source: National Marine Manufacturers Association, 2002 U.S. Recreational Boat Registration Statistics). Section 12.1 has been revised to make clear that the figures presented are based on the NSRE only.*

Pages 226 and 227: Have a very brief explanation that warmer temperature will increase demand for water-based recreation. On page 231, the report goes on to state that because of the increase in demand the state should capitalize by providing more opportunities for water-based recreation. The example they give is that we should develop new access points for stream and river-based recreation and/or build new reservoirs. As you know, we already have nearly 1,000 public boating access areas in the Commonwealth. This report assumes that public access is insufficient and that we need to develop more. Building more reservoirs will result in more boating opportunities but at what cost? Dams block fish passage. They are bad for the environment, dangerous to boaters and swimmers, and very expensive to build and maintain. I realize that this is not a comprehensive report on boating but to make such conclusions with the data presented in this report is questionable.

Response: *While Pennsylvania does have a relatively high density of streams and rivers, compared to the national average, it has a lower than average density of lakes and reservoirs. A discussion of the water resources in Pennsylvania has been added to Section 12.9. While the draft report did mention caveats regarding the building of additional reservoirs, those have been made more explicit in Section 12.9 of the revised report, and now include some of the specific issues raised by the commenter. Section 12.10 explicitly calls for research on whether the demand for water-based recreation is being met by current water resources or will be met in the future.*

There is no discussion of the impact on ice fishing or the recreational implications of invasive species that will be more likely to be a problem in Pennsylvania with a warming climate.
Response: *A new section, Section 12.3.3, has been added that discusses impacts on ice fishing in Pennsylvania. A discussion on the impact of climate change on invasive species, and subsequently on recreation, was not added because it is very difficult to predict what, if any, those impacts might be. A warmer climate might favor a different mix of invasive species, but it is not clear whether that mix would be more or less disruptive to recreation.*

Page 231: Second paragraph states that where wild trout populations are no longer viable trout stocking can replace natural productivity to some extent. Currently the Pennsylvania Fish and Boat Commission is raising the maximum number of adult trout possible from their production facilities. There is no room to make up for loses of wild trout populations with hatchery trout under the current production capabilities in the state.
Response: *The department agrees with the comment, and revisions have been made to Section 12.9.*

PFBC disagrees with the conclusion that climate change is not expected to reduce the total quantity of fishing resources in the state. If waters warm and the habitat become unsuitable for coldwater fish it is more likely that transitional fish (shiners, darters) would move in. If the water warms enough for warm/cool water fish such as rock bass, redbreast and smallmouth bass it is unclear if the other physical habitat would be sufficient to support populations robust enough to support recreational fishing.
Response: *The specific conclusion mentioned (in Section 12.3.2) has been modified. The authors agree that some waters that are currently suitable for coldwater fishing may not be suitable for warmwater fishing. Text has been added to make this point in Sections 12.3.2 and 12.9. Section 12.11 calls for research to identify which waters would be impacted by climate change, and how they would be impacted.*

PA GAME COMMISSION

The PGC has no specific issues from our agency regarding this section. When it involves the forest resources, there is a relative absence of detailed discussion on impacts to birds and mammals as well as herps which utilize public and private lands in the Commonwealth. There was no detailed specific discussion on existing negative impacts from listed invasive species, including plants, animals, insects etc. regarding habitat

management resolutions for the predicted impacts which vary considerably based on combined model results.
In general, we are seeing a northward shift of heat tolerant or cold-intolerant species and the report seems to indicate that. Also the report in this section was non-specific on measurements and changes that might occur to the habitat landscapes as to causation. If the predicted temperature changes failed to occur and temperatures stayed relatively the same as today, we will still see large scale plant species and habitat changes due to invasive species spread. These forest plant species change as a result of insect damage due to transport both by interstate and intrastate human travel and commerce. Additionally, improvements to forest stand species diversity are currently occurring based upon a reduction in deer herbivory statewide as surveyed by US Forest Service plot observations of browse survey stem counts. These presently occurring habitat changes have nothing to do with climate change directly and should be addressed by any such baseline establishment and measurement system currently being initiated, proposed or studied for model improvements and specific habitat model predictions.
Response: T*he department acknowledges detailed and specific discussion on these topics is beyond the scope of the report. The department has strived to provide the best possible product while adhering, as closely as possible, to the statutory timeline of Act 70 while also recognizing the opportunity afforded by the Act to update this work on a consistent and subsequent basis.*

PUBLIC UTILITY COMMISSION

PAGE NO.	PARA/LINE NO.	RECOMMENDED CHANGE
169	Third Para/ Line 8	We believe "kcf" should probably be "mcf"?
169	Third Para/ Line 9	We have to question the statement about only two major interstate gas pipelines serving the state. We have Tennessee, Tetco, Transco, Columbia Gas/Columbia Gulf tandem.
170	Both Charts	For clarity, the charts should be switched because the preceding paragraph starts out talking about the information on the second chart and then talks about the information on the first chart.
170	Both Charts	Increase font size in pie charts.
170	Both Charts	Indicate a year in which these statistics apply.
171	---	This page is blank; should be deleted.
172	First Para/ Line 2	Is there a reason 2006 data was used for the consumption charts? 2007 data is available and 2008 data may be available. Seems the report should use more current data where available.
173	Figure 10.4	Same comment as for Page 172 on the electricity sector consumption chart. Add in 2007 and 2008 data if available.
174	Figure 10.5	Monthly Use Chart – use more current data.

PAGE NO.	PARA/LINE NO.	RECOMMENDED CHANGE
174	Lines 6, 7 & Footnote	Duquesne decided not to join MISO.
175	First Para.	Suggest inserting "service" after load following". Table 10.1 – align the numbers in the columns. Suggest using the same units in the middle column.
176	First Para/ Line 2	Residential should be changed to commercial. See Page 172 – commercial +50%; residential +33%
177	Figure 10.8	Year of data is not stated. Suggest adding this to the title of the graph.
179	Last Para/2nd sentence	It might be appropriate to state assumptions regarding increased use of electricity with higher temperatures. If housing stock insulation is improved and shell leakage is reduced and/or A/C unit efficiency is increased substantially, electricity use may not increase. It is also not clear what the various scenarios are. It would have been helpful to have a short description of these scenarios in this section.
180	Line Chart	Vary colors—some are too light.
182	First Para/ Line 9	Cost of electricity – wholesale? retail? Just generation or G-T-D cost?
187	Fig. 10.15	Units on bottom need an added "0" of Figure 10.15.
190	Fourth Para/ Line 2	Remove first "power" from "…power excess power…"
190	10.4.2.3/ First Para.	Cogeneration is a distributed resource, which has the added benefit of reducing the need for some future transmission and distribution investments. (10.4.2.3, first paragraph)
191	First Para.	There is no prohibition in PA on self generation including micro-grids. Utilities have exclusive rights to provide service but that does not preclude one from generating their own electricity. This paragraph needs to be reworked.
General Note		Studies on the impact of a price on carbon would have on electricity prices – Did not get the impression that the squeezed margins on coal plants adequately covered the impact on fixed cost recovery associated with future emissions investments. The point is made, based on the assumed gas prices and coal prices, that coal would remain competitive from a marginal cost perspective—but it is less clear if these old plans can continue to cover significant plant repair and emission investment costs. Some may fall out, impact the stack and therefore, electricity prices in a more severe way.

Note*: The author has revised the report to address all of the comments. The page numbers in the comments refer to the draft report of Chapter 10, Energy. The comments have been addressed within pages 184 to 216 of Chapter 10 in the revised report.*

Response to Comments on pages 172 – 174: *Where data was available, the data was updated to 2007. Data from EIA later than 2006 is not available until August. In Figure 10.8, data was changed to PJM data from 2007. In Figure 10.4, data was changed to DOE data from 2007.*

Response to Comment on page 179: *Figures 10.11 and 10.12 were revised based on the comment. A note in the text on page 194 and in the Appendix was added. An estimated baseline of how electricity demand is likely to change in the face of warmer temperatures was studied in the absence of specific policies. Policy recommendations are not within the scope of this report.*

Response to Comment on page 191: *The paragraph on page 209 was rewritten and clarified to say that Pennsylvania statute does not define "micro-grid." In the absence of a definition, there may be barriers to adoption due to additional steps and requirements from the Public Utility Commission.*

Response to General Note: *On page 200, the report was revised. It is possible that a fixed price on carbon emissions would affect fixed capitol cost recovery.*