

Purdue Climate Change Research Center

---

# Impacts of Climate Change for the State of Indiana

Prepared for: The Honorable Richard G. Lugar

Prepared by: The Purdue Climate Change Research Center

February 2008

## Executive Summary

We have analyzed the potential “no-action” impacts of climate change on the State of Indiana, as well as the potential opportunities and consequences of climate change mitigation in the State. Most of our analyses of no-action impacts assume future greenhouse gas concentrations at the high end of the IPCC SRES illustrative emissions scenarios, although some analyses also consider low emissions trajectories. Further, some of our analyses are quantitative based on published and unpublished work that is ongoing at Purdue University, while other analyses are qualitative based on “expert opinion.” While further research will always bring further clarity, we hope that these initial analyses provide a reliable indication of the direction and magnitude of important climate change impacts and opportunities in Indiana.

### ***Should greenhouse gas concentrations continue to increase, Indiana faces a number of potential impacts:***

- The occurrence of extreme hot events is likely to increase in Indiana, while the occurrence of extreme cold events is likely to decrease.
- The occurrence of conditions that spawn severe thunderstorms is likely to increase in Indiana.
- Annual average precipitation is likely to increase in the region, as is the occurrence of rain during the winter and early spring, resulting in higher streamflow and an increased likelihood of flooding.
- An increase in the frequency and intensity of summer storms is likely to increase the frequency of flooding events and exacerbate summer soil moisture deficits in Indiana.
- Vulnerability of soils to dry winters could increase the risk of multi-year droughts in Indiana.
- The corn belt will likely remain the best area for corn and soybean production and Indiana will likely maintain its position as a top producer of those crops.
- Heavier rainfall and periodic flooding during planting and harvest periods may lead to crop losses in Indiana, as well as increased pest and disease burdens.
- The pace of climate change relative to the rate of technological change will be an important determinant of agricultural impacts and outcomes in Indiana.
- Climate change could have deleterious affects on mussels, fish and amphibians in Indiana, several of which are endangered. There exist considerable uncertainties as to how climate change may impact bird life histories and distributions in Indiana.
- High value hardwoods are potentially threatened in Indiana.
- Should climate in Indiana shift to “hotter, drier summers” and “warmer, wetter winters,” the loss of soil organic matter is likely to increase.

- Decreases in cold-related health stress in Indiana could overcome increases in heat-related health stress. However, the occurrence of air stagnation events is likely to increase in Indiana, potentially increasing the occurrence of pollution events that impact human health.
- Decreases in heating demand in Indiana could overcome increases in cooling demand. However, quantification of how these changes in demand will influence actual energy usage and emissions requires further analysis.

***Indiana faces potential opportunities and consequences in emerging carbon offset markets:***

- Purdue University has produced a highly detailed inventory of all fossil fuel carbon dioxide emissions for the United States and the state of Indiana. This will meet many of the climate registry goals of S.2191. This is a key contribution that the state can make to the integrity of this legislation.
- Indiana has considerable opportunity to accrue offset credits in the agricultural sector. Many of these opportunities come with co-benefits. However, some of these credits depend upon the opportunity cost of cropland.
- Land cover changes created by offset markets could directly alter surface climate in Indiana.

This document reflects the analysis, understanding, and opinions of the authors, and does not reflect official policy of Purdue University.

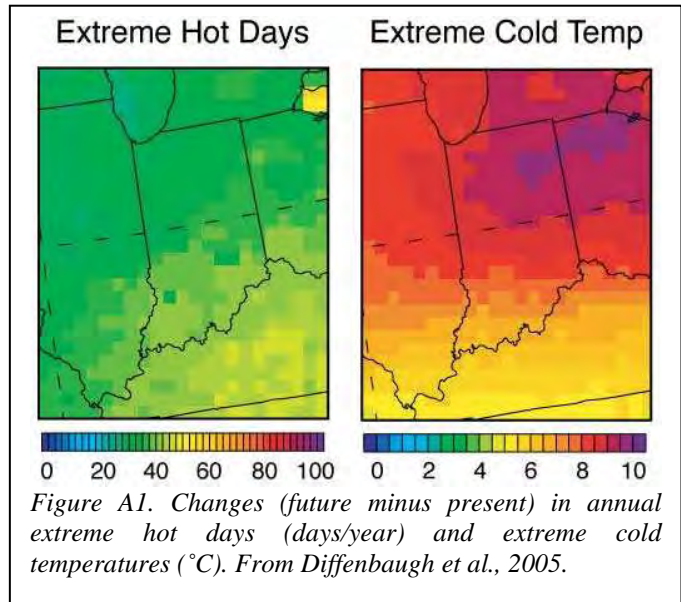
## A. Likely Climate Changes in Indiana

Noah Diffenbaugh, Dept. of Earth and Atmospheric Sciences; Michael Baldwin, Dept. of Earth and Atmospheric Sciences; Robert Trapp, Dept. of Earth and Atmospheric Sciences

### Temperature

The occurrence and duration of extreme hot events is likely to increase throughout the United States should greenhouse gas concentrations continue to rise (e.g., (Diffenbaugh et al. 2005)). In Indiana, temperatures that now occur during the hottest two-and-a-half weeks of the year are likely to occur for seven to ten weeks ((Diffenbaugh et al. 2005), and Figure A1). The increases in southern Indiana represent an increase of more than 200% (or a tripling) over present conditions.

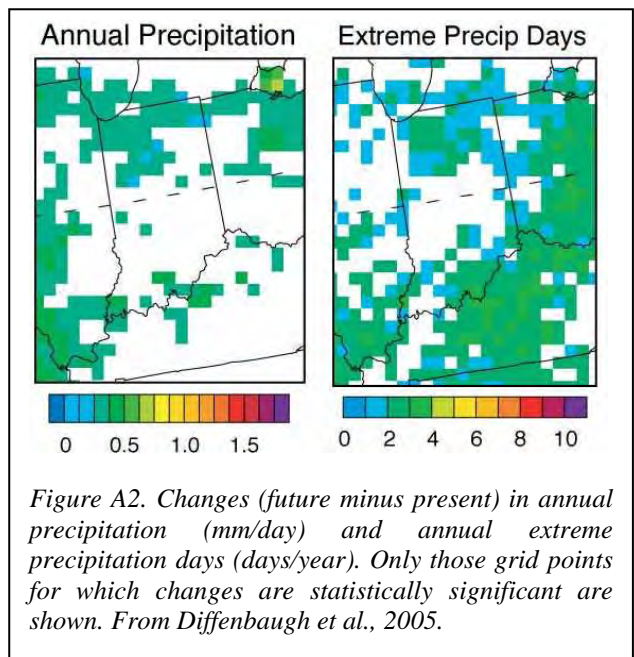
Conversely, the frequency and severity of extreme cold events is likely to decrease throughout the United States (Diffenbaugh et al. 2005). Indiana could see some of the largest warming of extreme cold temperatures, with the coldest events of the year warming by up to 10 °C by the end of this century under the SRES A2 emissions scenario ((Diffenbaugh et al. 2005), and Figure A1).



### Precipitation

Total annual precipitation and extreme precipitation are likely to increase over much of the United States should greenhouse gas concentrations continue to increase (e.g., (Diffenbaugh et al. 2005)). Total annual precipitation could increase up to 20% over northern Indiana (see Figure A2). Extreme precipitation events could increase up to 40% over northern and southern Indiana.

We have also conducted the first quantification of the potential response of severe weather environments in the United States to anthropogenic increases in greenhouse gas concentrations (Trapp et al., 2007). We find that the conditions that spawn severe



thunderstorms increase throughout much of the United States, and particularly east of the Rocky Mountains.

Over Indiana, summer occurrence increases 1 to 3 days per year in the future climate (Trapp et al., 2007, and Figure A3). The increase in total warm-season occurrence over Indiana reaches up to 50 % relative to the present conditions. In the Midwest, these increases in severe weather environments occur largely during what is now the peak severe weather season (Trapp et al., 2007, and Figure A4).

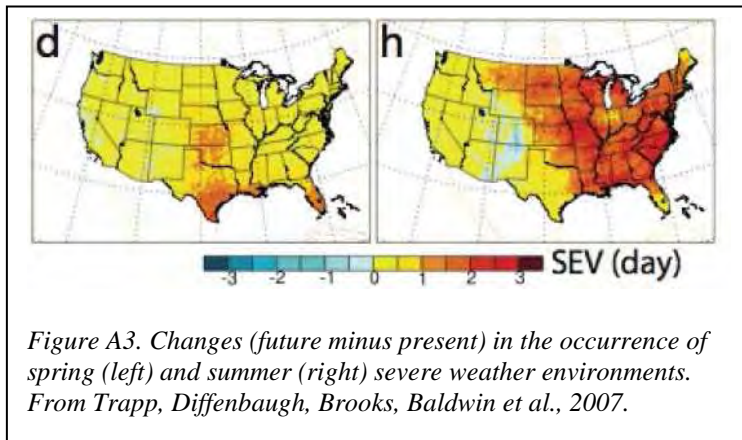


Figure A3. Changes (future minus present) in the occurrence of spring (left) and summer (right) severe weather environments. From Trapp, Diffenbaugh, Brooks, Baldwin et al., 2007.

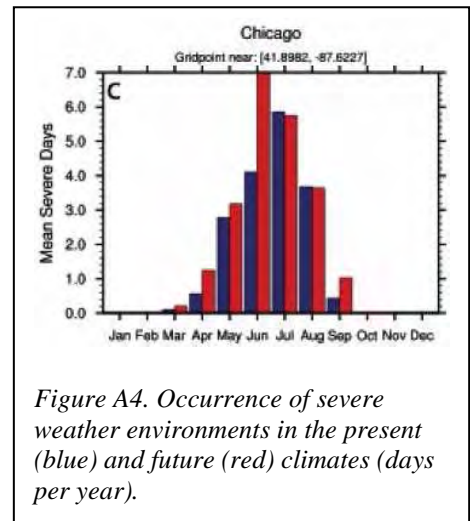


Figure A4. Occurrence of severe weather environments in the present (blue) and future (red) climates (days per year).

## B. Likely Impacts of Climate Change on Water Resources in Indiana

Keith Cherkauer, Dept. of Agricultural and Biological Engineering

### Annual and seasonal precipitation

While precipitation is likely to increase on an annual average basis, there is likely to be a shift in the seasonality of that precipitation, with winter and spring precipitation increasing by 21 and 30% by the end of the century, and summer precipitation declining by up to 9% (Figure B1). Such a shift may result in the increased precipitation being of minimal use to crops but of significant concern for flooding. Wetter winters, the product of more precipitation and warmer air temperatures, may result in an increased frequency of floods like that on the Tippecanoe and Wabash Rivers this past January (Figure B2) a direct result of the ~100mm (~4in) of precipitation that fell within 24 hours. Reduced summer precipitation may impact crop growth, though the overall change in quantity is not great (a maximum forecasted decrease of 25 mm (1 in)). A bigger concern may be in the timing of that precipitation. Several sources forecast an increase in severe weather in the area (e.g. Kling et al. 2003), which would produce more intensive rainfalls, contributing to increases in summer flooding while leaving soils even drier.

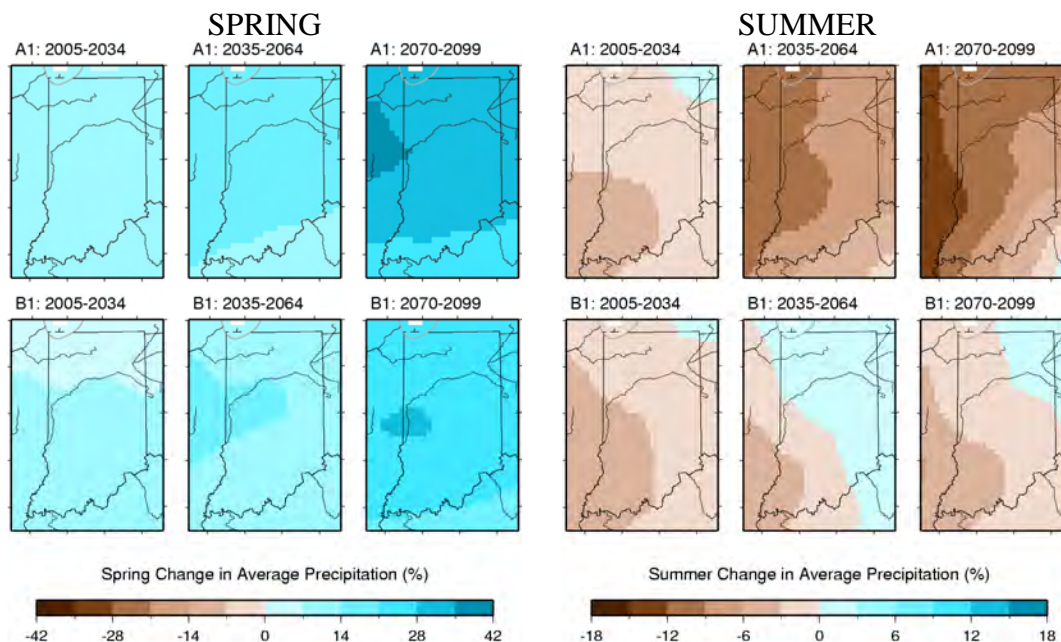
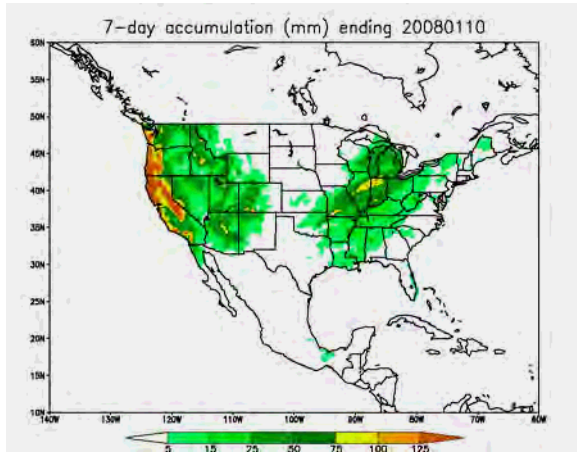
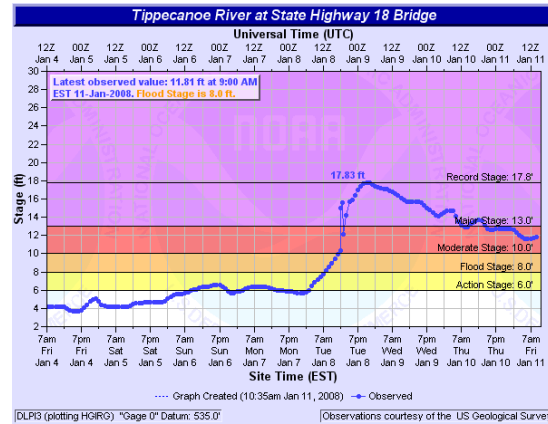


Figure B1. Projected changes in annual average spring and summer precipitation (in units of percentage change relative to 1961-1990 averages) as simulated by the VIC hydrological model under the higher (A1) and lower (B1) emissions scenarios. Results shown are the average of VIC model simulations driven by downscaled output from the GFDL, HadCM3 and PCM climate models.

## 7-day Precipitation Map



## Tippecanoe River discharge



## Norway Bridge, White County



## IN 225 Bridge, Tippecanoe County

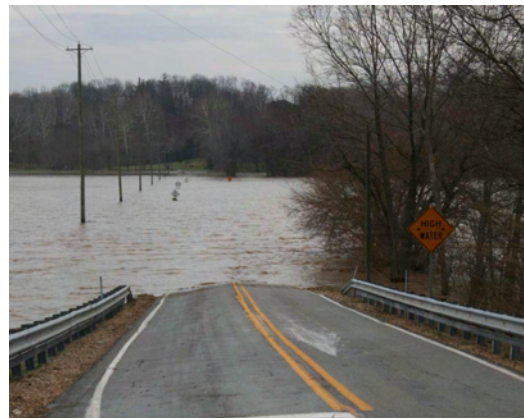


Figure B2. Images from the Tippecanoe River flood of January 2008: (a) 7-day precipitation accumulation showing the between 75 and 100mm of precipitation in the river basin, most falling on January 8, 2008 (Source: National Weather Service); (b) Tippecanoe River discharge at the downstream most station in the days after the flood peak (Source: National Weather Service); (c) Norway Bridge over the Tippecanoe River in White County; and (d) Indiana 225 bridge over the Wabash River near Battle Ground.

## Winter Processes

As winter temperatures have warmed across the region, more precipitation has been falling as rain and less as snow, though only the decrease in northern Indiana has been found to be statistically significant (Sinha and Cherkauer, 2008). This suggests that despite increased winter air temperatures, snow accumulation has remained relatively constant because of increases in winter precipitation. Additionally at the same northern Indiana location the occurrence of soil frost has increased significantly. This is likely a short-term response to the decrease in surface insulation afforded by thinning snow cover. As air temperatures continue to increase this effect is expected to reverse itself leading to a decrease in seasonally frozen soil.

Climate projections suggest that the number of days with snowfall and the amount of snowfall is not going to change significantly in the future (Kling et al. 2003) as winters will be wetter so the frequency of precipitation and freezing temperatures occurring simultaneously will remain about the same as it has been historically. However, increased air temperatures will reduce the length of time that snow cover is present in the state by between 11 and 16 days by the end of the century (Figure B3). The first day of snow cover will come on the order of two weeks later and the last day of snow cover will arrive about two weeks earlier by the end of the century (Figure B3).

While there is the potential for soil frost to become more significant in the near future because of the reduction of snow cover, by the end of the century the number of days with soil frost will be reduced by between 37 and 56 days (Figure B3). Soils will first freeze substantially between one and three weeks later than they currently do. Thaw, which is an important part of having soils ready for planting in the spring, will shift earlier by two to almost four weeks (Figure B3).

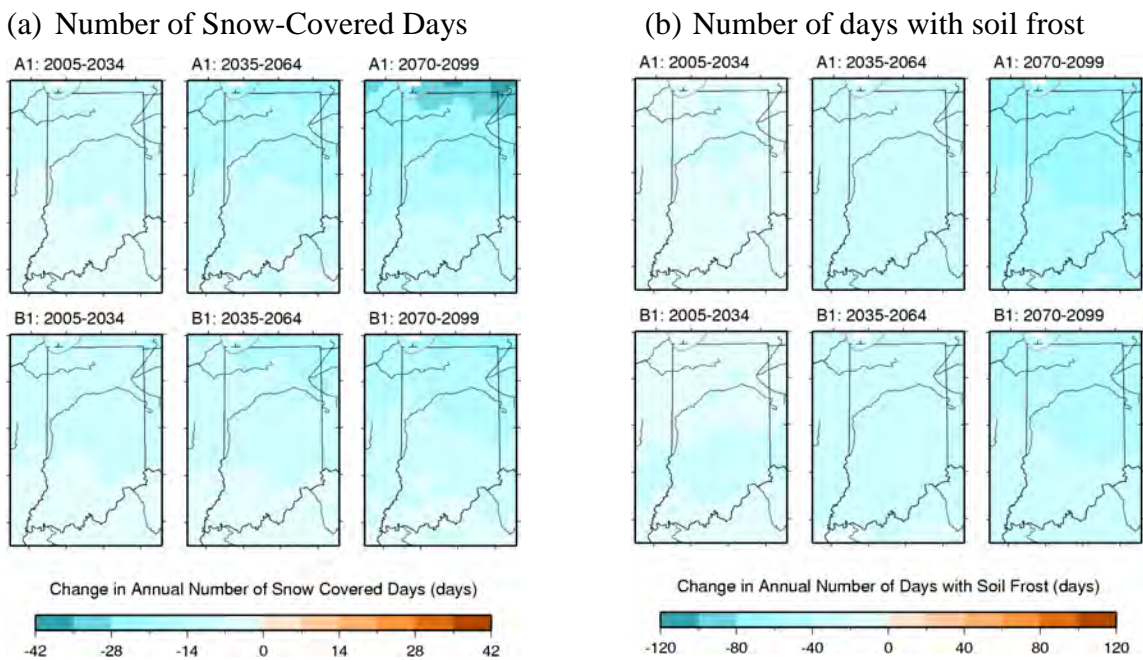


Figure B3. Projected future change in (a) the number of snow-covered days per year, and (b) the length of the soil frost season, relative to the 1961-1990 average for the higher (A1fi) and lower (B1) emission scenarios as simulated by the VIC model driven by downscaled projections from the GFDL, HadCM3 and PCM models.

### Evapotranspiration

Changes in annual average evapotranspiration (ET) are projected to be small, on the order of a 1% increase. The magnitude of this change is very important as it controls how much of the increased precipitation is left to refill soil moisture levels and contribute to increases in streamflow. Such a small change is attributed to more water being available in the winter and spring when ET rates are low and soil moisture is typically high, so changes will be minimal.



The fact that ET is projected to increase is a testament to increases in spring ET and wetter soils in early summer alleviating some if not all of the effects of drier summers.

Total runoff

Total runoff, the sum of direct surface flow and baseflow (groundwater return flows), is the amount of water available for streamflow. It is projected to increase annually by between 25 and 38% (Figure B4) by the end of the century. Seasonally, the largest percent increases (33-59%) in total runoff occur in the winter and spring (32-39%), however, the spring increase is nearly double the volume of the winter increase. Summer total runoff is also projected to increase by 24%, but this is due to increases in baseflow (33-37%) resulting from a wetter spring. Summer surface runoff actually decreases by up to 8%. Changes in autumn total runoff are mixed and highly susceptible to the amount of precipitation received in the summer, so changes in autumn flow are a direct reflection of whether summer ended with enough precipitation to compensate for evaporative losses.

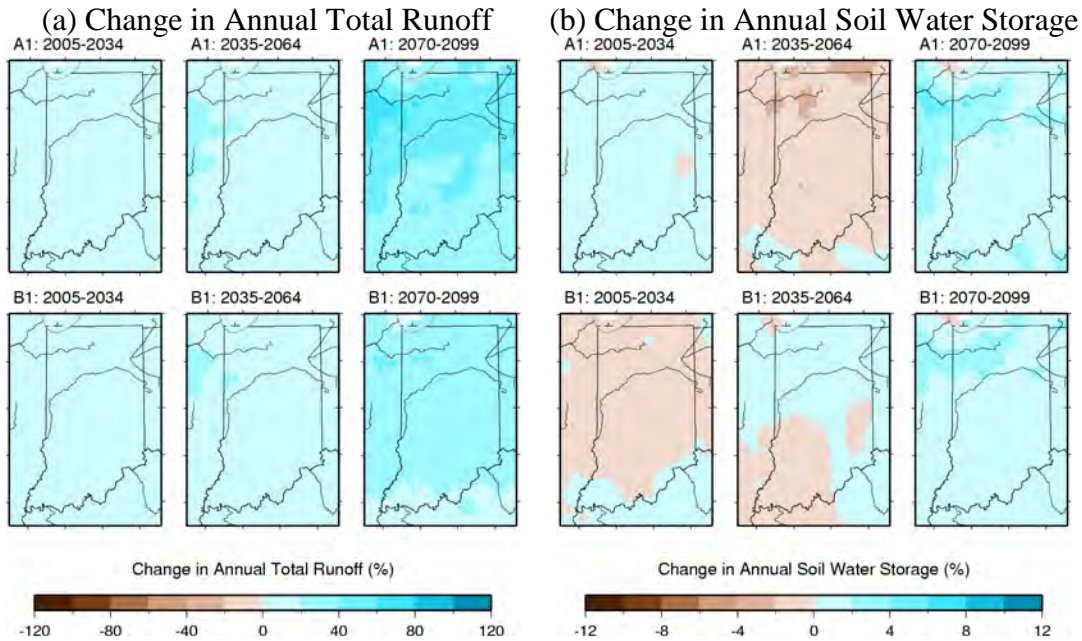


Figure B4. Projected future change in (a) cumulative total runoff, and (b) soil column moisture. Projected changes shown relative to the 1961-1990 average for the higher (A1fi) and lower (B1) scenarios as simulated by the VIC hydrological model driven by downscaled projections from the GFDL, HadCM3 and PCM climate models.

Soil moisture

Storage of water in the soil column is projected to increase by only 1-2% annually by the end of the century (Figure B4). Autumn soil moisture storage is projected to decrease or stay the same by the end of the century, while the other three seasons may see increases of up to 2.4%. Winter and spring soil moisture reflect both the increase in precipitation, but also the reduction of snow cover and soil frost which will increase infiltration throughout both seasons. The increase in summer soil moisture is a reflection in the wetter conditions in spring and early summer. Increases in autumn and winter precipitation mean that soil moisture has generally recovered from autumn deficits prior to the following spring, but if precipitation is on the low end during these seasons, the potential for multi-year drought increases.

The distribution of daily flows (Figure B5) shows that flows increase most substantially in the spring. Winter flows also increase significantly, but continue to be smaller than spring flows.

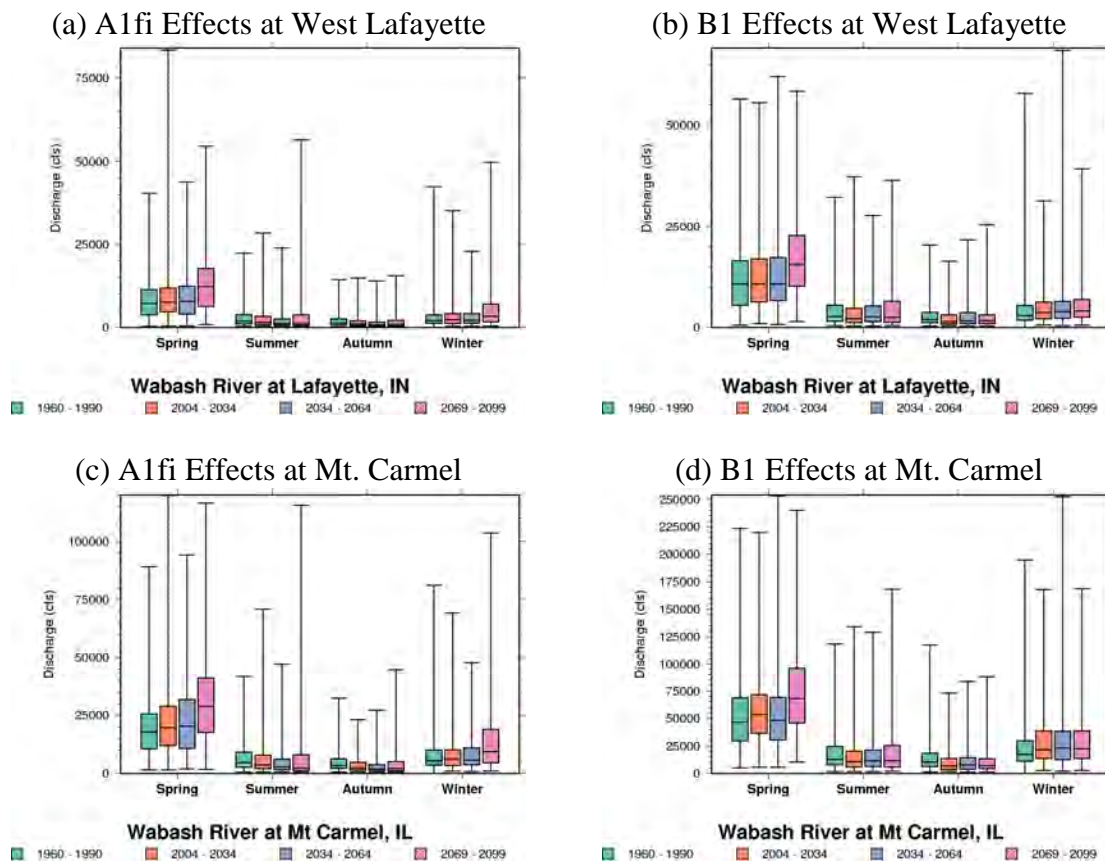


Figure B5. Projected future change in daily streamflow distributions for the Wabash River at West Lafayette (a) and (b) and the Wabash River at Mt. Carmel (c) and (d). Box indicates the 1<sup>st</sup> and 3<sup>rd</sup> quartiles, with the internal line indicating the annual mean. The whiskers indicate the maximum and minimum values. Streamflows are for the higher (A1fi) and lower (B1) scenarios as simulated by the VIC hydrological model driven by downscaled projections from the GFDL, HadCM3 and PCM climate models.

Summer and autumn flows do not change significantly, or consistently between model simulations. The one exception being that summer maximum flows increase for the Wabash for both gauge sites and both future change scenarios.

The trends shown here agree with projections made for large river basins throughout the United States (Milly et al. 2005), where 62% of 24 climate projections indicate that the Ohio River basin will experience an increase in runoff of 5 to 10% by the period 2041-2060. The upper Mississippi River is also projected to experience runoff increases, but by only 2 to 5% and the Great Lakes region is not expected to experience any significant change. The latter result contributes to the minimal drop (at most 2 ft) in lake levels projected for Lake Michigan in the current century.

## C. Likely Impacts of Climate Change on Agriculture in Indiana

*Gerald Shively, Dept. of Agricultural Economics; Otto Doering, Dept. of Agricultural Economics; Noah Diffenbaugh, Dept. of Earth and Atmospheric Sciences; Laura Bowling, Dept. of Agronomy; Christian Krupke, Dept. of Entomology; Bryan Pijanowski, Dept. of Forestry and Natural Resources; Jeff Holland, Dept. of Entomology; John “Barney” Dunning, Dept. of Forestry and Natural Resources*

### Overview

Indiana is among the top US producers of corn and soybeans. Under all likely climate scenarios, the corn belt will remain the best area for corn and soybean production and Indiana will maintain its position as a top producer of these crops. The state also has important production of other crops, and also of poultry and livestock. Predicting the impact of climate change on these systems is somewhat more difficult because less research attention has been focused on these parts of the agricultural industry.

The major climate-related drivers of agricultural outcomes will be changes in (i) atmospheric CO<sub>2</sub> and nitrogen, (ii) temperature, (iii) precipitation, (iv) pests and pathogens, and (v) extreme events.

- Projected increases in temperature will increase the length of Indiana's growing season. This, combined with increases in atmospheric CO<sub>2</sub> and nitrogen will increase the productivity of most annual crops, including corn and soybeans. Livestock populations may be stressed due to higher temperatures, especially during warmer summer months.
- As highlighted in other parts of this report, the distribution of precipitation across the year is expected to shift, leading to wetter winters and dryer summers. In addition, the inability of rainfall to compensate for increased heat may lead to more drying. This is likely to be most pronounced in summer, leading to dryer soils and more drought-like conditions. To the extent the agricultural industry is unable to compensate through the development of improved genetic varieties that exhibit drought tolerance, productivity will decline. Although one might expect irrigation to fill water needs, given current crop genetics, and associated rates of crop evapotranspiration, investments in irrigation infrastructure are not likely to compensate for the combined forces of greater heat and less moisture. As a result, the key adaptation mechanisms for farmers will be to shift planting dates and adopt crop varieties with shorter growing seasons so as to avoid the hottest parts of the growing season. Farmers will have to avoid the deleterious effects of climate change and take advantage of climate conditions that are more conducive to crop growth. Heavier rainfall and periodic flooding during planting and harvest periods may lead to crop losses.
- Climate changes are likely to allow more successful overwintering of several pests and diseases, and to also allow for the expansion of pests and pathogens. Heat and moisture stress can make crops and animals more susceptible to pests and diseases. To some extent, improvements in crop and animal genetics may compensate.
- Increases in extreme rainfall and heat events are likely. These will stress crop and livestock systems above and beyond the impacts listed above. Extreme rainfall events may lead

to greater soil erosion and agricultural runoff, with concomitant increases in off-site damages associated with sediment, nutrient, chemical, and pathogen loads. These effects are discussed elsewhere in this report.

- Although perennial systems (e.g. fruit trees and grape production) are not a large part of Indiana agriculture, they are locally important in some areas. By virtue of their permanent nature, producers may find it more problematic to adjust their production practices. As a result, these systems may be more vulnerable to the stresses outlined above.
- Technology responses, especially development of new crop genetics, will be key conditioning factors. The pace of climate change relative to the rate of technological change will be an important determinant of agricultural impacts and outcomes.

### Crop Phenology

The VIC model, in this case forced with only the HadCM3 future climate projections and coupled to a simple crop growth model, is used to assess changes in earliest planting date and growing degree days. Earliest planting dates are based on when air temperature has been  $> 10^{\circ}\text{C}$  ( $50^{\circ}\text{F}$ ) for 5 or more days, soil temperature has been  $> 12.8^{\circ}\text{C}$  ( $12^{\circ}\text{F}$ ) for 3 or more days, and soil moisture has been  $<$  field capacity for 3 or more days. Additionally, rain cannot occur on the date of planting. Growing degree days are based on accumulated temperatures in excess of  $10^{\circ}\text{C}$ , and must exceed 1250 for typical corn crops.

Changes are best interpreted relative to the model base climatology; in general there is little difference between the A1 and B1 scenarios by mid-century. Planting dates show the greatest change in the northern part of the state, probably due to soil moisture (Figure C1). Possible planting dates move forward by about 1 week by mid-century, 1-2 weeks by century end. For the base period (1960-1989), planting never occurs in a few years indicating some problems with model setup. Changes in crop maturity dates follow the patterns and magnitudes of planting changes, by mid-century maturity advances by 5-10 days.

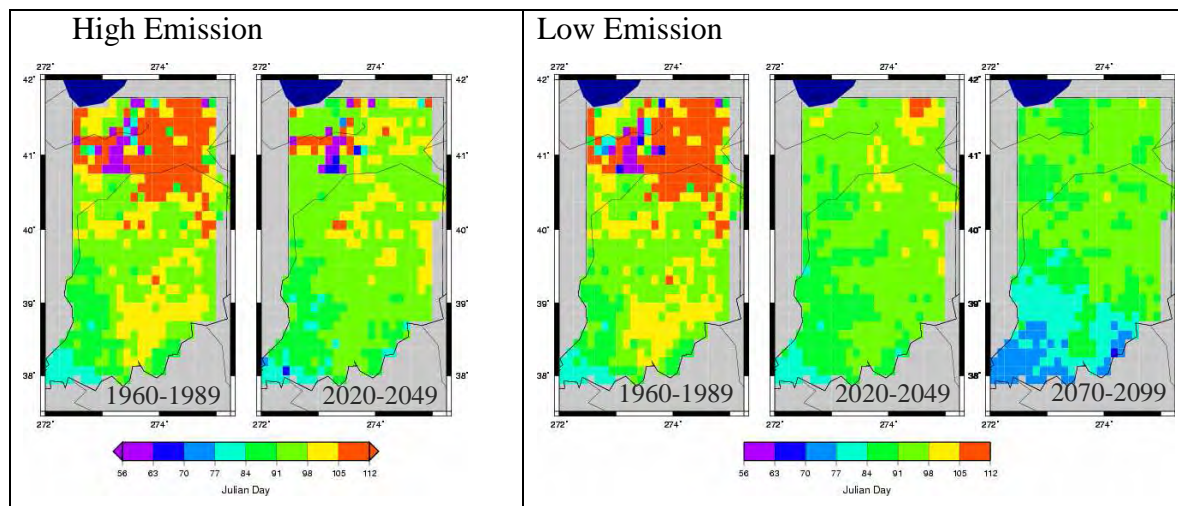


Figure C1. Earliest planting date as simulated by the VIC model driven by downscaled projections from the GFDL climate model (a) A1fi and (b) B1 scenarios.

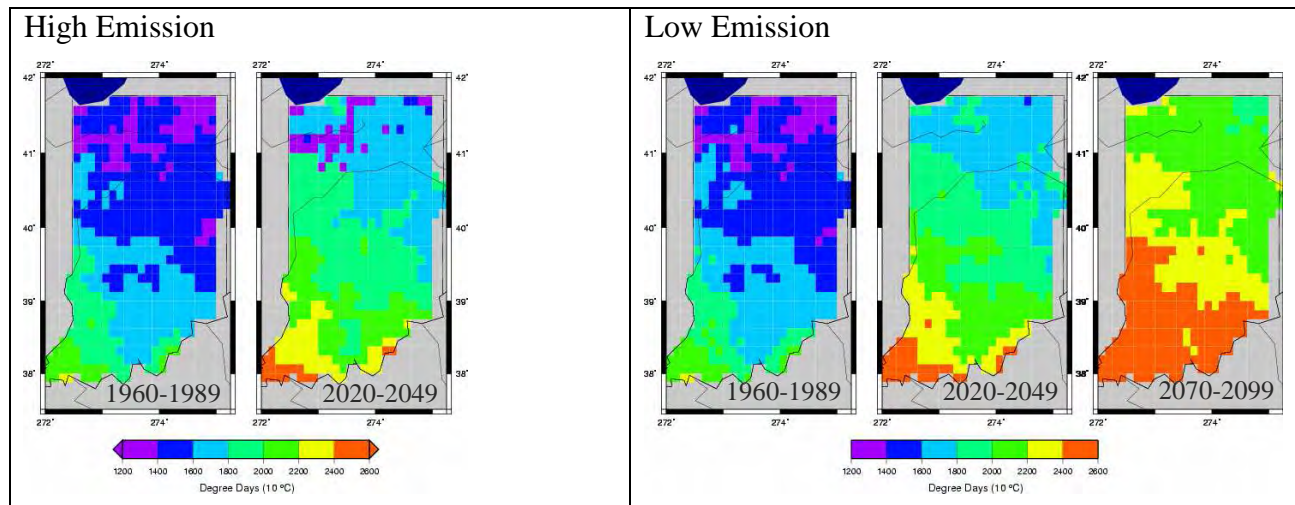


Figure C2. Growing degree days ( $\times 10$ ) as simulated by the VIC model driven by downscaled projections

Total growing season length (gdd10, accumulated until soil frost) increases by 200-400 degree-days by mid-century and 400 degree-days by century end (C2).

Besides the previously mentioned problems with crops not getting planted in some years, these preliminary simulations also had difficulty triggering harvest in almost all years for all periods. This suggests that hydrometeorological prediction of harvest needs significant work, but may also indicate potential problems with adequate drying of crops under future climate scenarios. Additionally, these simulations do not account for changes in hybrids or crop types that might result from adaptation to climate changes.

#### Effects of Temperature Extremes

Changes in the distribution of daily temperature and precipitation events can lead to widespread changes in the exceedance of critical thresholds (White et al. 2006, Diffenbaugh et al. 2007, Trapp et al. 2007). Indeed, recent modeling of the effects of 21<sup>st</sup>-century climate change on agriculture suggest that changes in the occurrence of severe events could be the primary driver of crop response, with agricultural yields showing little sensitivity to projected changes in mean growing season temperature and heat accumulation but dramatic sensitivity to the coincident changes in temperature extremes (White

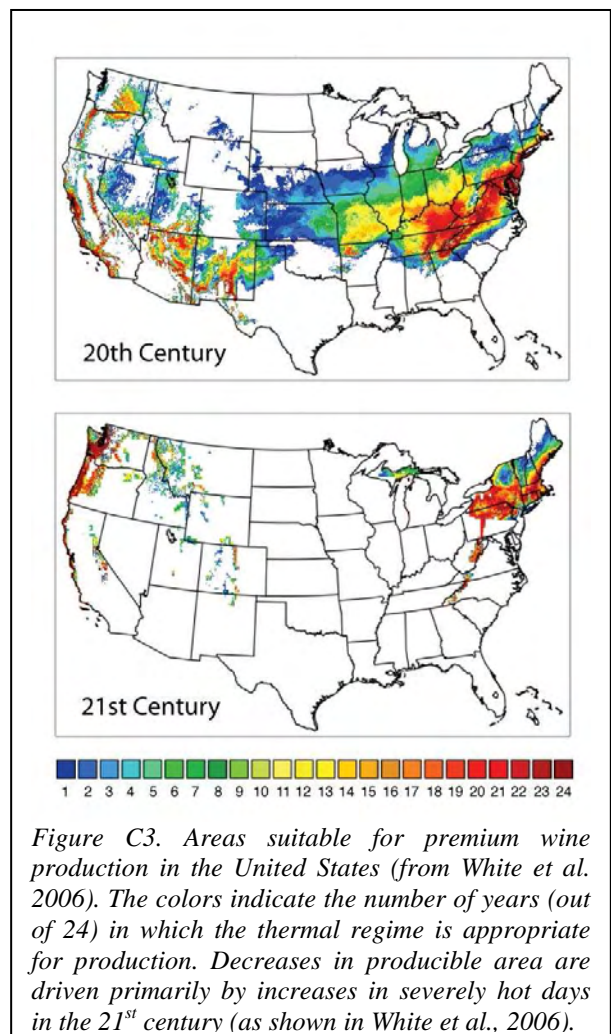


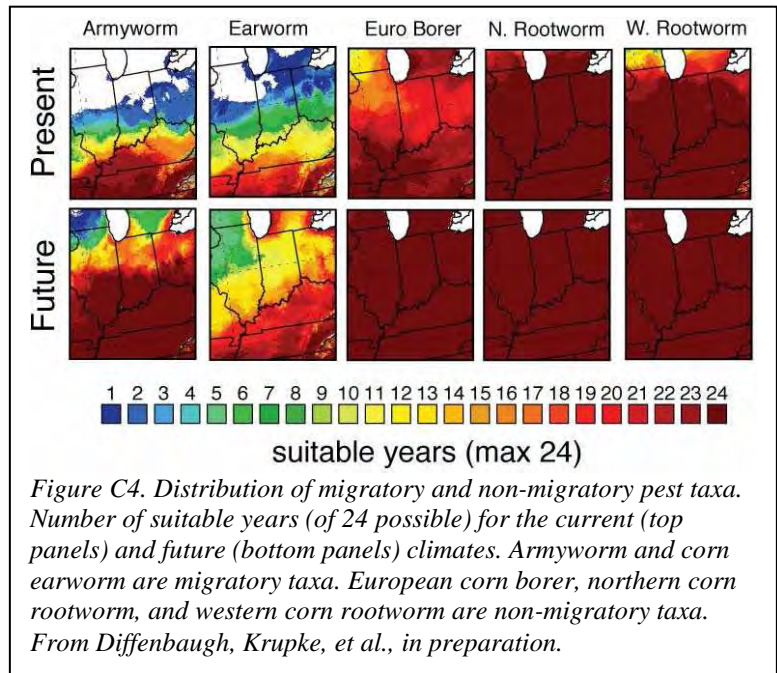
Figure C3. Areas suitable for premium wine production in the United States (from White et al. 2006). The colors indicate the number of years (out of 24) in which the thermal regime is appropriate for production. Decreases in producible area are driven primarily by increases in severely hot days in the 21<sup>st</sup> century (as shown in White et al., 2006).

et al. 2006). This point is illustrated in Figure C3, where the top panel shows the suitability of wine production in the US under present temperature conditions, and the bottom panel shows the suitability under anticipated future changes in temperature. Under the latter, the scope for high quality winegrape production is dramatically reduced. This reduction is driven primarily by changes in the temperature extremes, with changes in mean temperature GDD causing little change in production (White et al., 2006).

### Agricultural Pests

Many of the most important agricultural pests are insects, along with many species that pollinate crops, increase soil fertility through decomposition, and prey upon crop pests. Insect pests reduce US crop production by 13% for an annual loss of \$33 billion (USBC 1998). The increase in plant stress predicted with climate change will lead to reduced plant resistance to insect herbivores and an increase in loss. Because different aspects of the climate are not expected to shift in the same way (Williams et al. 2007), the impact on agriculture will not be easily forecast (Paine et al. 1998). For example, increased CO2 levels can increase the losses of soybean to the invasive Japanese beetle (Hamilton et al. 2005). The large majority of our crop pest insects are invasive species. The exotic insects such as soybean aphid and the emerald ash borer that successfully invade the Midwest are those that come from similar climates. An altered climate regime in Indiana could invite an entirely new suite of invasive insects that we currently have no knowledge of. Forest insect pests, such as the gypsy moth, defoliate trees during the early summer. When combined with the stress of drought, trees are known to die (Pijanowski 1994). Warmer winter temperatures can also decrease forest pest over-wintering mortality in turn increasing the pest population levels during the summer (Sharov et al. 1999). In Indiana, loss of trees on private forest lands could have a large economic impact as these lands are often harvested and income by families during important times.

We have quantified the potential impacts of future climate change on a suite of Indiana corn pests (see Figure C4). We find that the distribution of these pests expands in Indiana for those pests that are not already prevalent throughout Indiana. In particular, the migratory taxa – armyworm and corn earworm – become substantially more prevalent in the future climate, transitioning from rarely or never present to commonly present. This expansion is driven by decreases in the occurrence of severe cold events, allowing these taxa to overwinter in Indiana. These migratory taxa happen to be the most cosmopolitan in their infestations, raising the possibility that the risk of infestation would likely increase for other crops in addition to corn should greenhouse gas concentrations continue to rise.



## **D. Likely Impacts of Climate Change on Plants and Animals in Indiana**

*Jeff Holland, Dept. of Entomology; Rueben Goforth, Dept. of Forestry and Natural Resources; Marisol Sepulveda, Dept. of Forestry and Natural Resources; Kevin Gibson, Dept. of Botany and Plant Pathology; Harmon Weeks, Dept. of Forestry and Natural Resources; Charles Michler, Dept. of Forestry and Natural Resources and the USDA Forest Service; Hardwood Tree Improvement and Regeneration Center; John “Barney” Dunning, Dept. of Forestry and Natural Resources; Rod Williams, Dept. of Forestry and Natural Resources; Kerry Rabenold, Dept. of Biological Sciences; Bryan Pijanowski, Dept. of Forestry and Natural Resources; Helen Rowe, Restoration Ecology Initiative, Purdue Center for the Environment; Patrick A. Zollner Department of Forestry and Natural Resources*

Plants and animals are particularly sensitive to climate variability and there are potentially several important species that could be impacted by future climate change in Indiana. In general, threats from climate change are likely to be manifested by declines or changes in behavior of native species, increased incidence of invasive species and/or increased risks of extinction of endangered/threatened species. Research on this topic (impacts of climate change on plant and especially animal distributions in Indiana or the Great Lakes in general) is sparse. Potential climate change impacts in Indiana by major taxonomic group are as follows:

### *Insects*

The possible affects of climate change on agricultural pests are addressed in the Agriculture section of this analysis.

An altered climate could also hamper efforts to bolster populations of endangered insects such as Karner’s blue butterfly and Mitchell’s satyr butterfly. Efforts to reintroduce species such as Hine’s emerald dragonfly and the American burying beetle could also be frustrated. Many additional insect species could face extinction under an altered climate if the necessary temperature conditions and necessary moisture conditions become separated in space (i.e., a no analogue future). Insect species are especially reliant on specific host plants, environmental conditions, and microclimates. If these necessary conditions shift locations, the species must be able to move across the Indiana landscape to track these conditions. Understanding how human land use impedes or facilitates the movement of beneficial or endangered insects will become increasingly important to avoid “filtering out” these species during such migrations.

Many insects cause disease in humans and pets. Warmer winters are normally associated with increases in the ability of pest species such as ticks to overwinter, and therefore milder winters may lead to an increase in tick-borne diseases such as Lyme disease.

### *Mussels*

Mussels in Indiana streams serve critical ecological roles as primary consumers, filter feeders, and detritivores, and they provide significant ecosystem services by acting as nutrient sinks (McMahon 1991). However, they are very susceptible to mortality as a result of increased water temperature regimes, decreased oxygen levels, lowered minimum flows, and large flood events, all of which are likely consequences of climate change (Gibson et al. 2005). Freshwater mussels are already among the most imperiled aquatic organisms worldwide (Bogan 1993, Williams et al.



1993), and of the 67 mussel species in Indiana, 10 are Federally-listed as endangered species. Stream and river environmental changes related to climate change will undoubtedly hasten the extirpation of Indiana's mussels from the State's waters, thus contributing to a significant loss of both natural history and ecological integrity.

### Fish

Immediate effects of global warming are likely to be felt most dramatically by cool and cold-water species. Indeed cold-water species, such as lake trout and brown trout, and even some cool-water fish, such as northern pike and walleye, may decline dramatically, potentially to the point where they disappear from the southern parts of the state. There is also concern about effects on the overall change in distribution of warm-water species. For example, the range of warm-water fish species, such as smallmouth bass and bluegill, is likely to expand northward. In addition, increases in water temperatures are likely to increase the spread of several pathogens and thus increase the incidence of fish die-offs, especially during the summer months.

### Amphibians

In extreme years reduced pond depth can increase exposure of amphibian embryos to UVB radiation. In controlled laboratory studies (Blaustein et al.), exposure to UVB radiation caused a 90% increase in mortality of embryos. In other studies, increase UVB exposure causes an increase to infectious diseases which in turn increases mortality (Kiesecker et al. 2001). In addition, warming of climate would increase surface water body temperatures thus altering important habitat for amphibians, especially those dependent on wetlands. One critical resource in Indiana is vernal pools in woodlands, which support breeding populations of many forest amphibians. These populations may disappear if vernal pools dry earlier, preventing amphibians from completing their aquatic life stage. The state-listed crawfish frog and the four-toed salamander are endangered species that could be adversely impacted by climate change.

### Reptiles

We know that many species of turtles, including those endemic to Indiana, have TSD (temperature-dependent sex determination). For example, eggs laid in soils that are kept cold produce males whereas warmer soils produce females. In Indiana, the Spotted Turtle, Ornate Box Turtle and Blanding's Turtle, have TSD (temperature-dependent sex determination). Janzen (1994) stated that an increase of 4C would effectively eliminate the production of male offspring.

### Birds

Impacts of climate change on bird populations are likely to include changes in abundance and distribution of some species, especially those whose northern or southern geographical limits occur in Indiana. Southern species like black vultures are likely to spread northward through the state, as northern species such as rose-breasted grosbeaks and veerys are likely to contract to the north, in part because plant communities that they inhabit will shift northward. More severe weather events, especially in winter, will create unpredictable pressures on rare species and species at their northern limits, like Carolina wrens. More species are likely to attempt to over-winter in Indiana habitats, changing the balance of competition for winter food; in the southeastern states, changes in wintering geese distribution is a leading cause of ecosystem stress on both the winter and breeding grounds.

Implications of the reshuffling of species in natural ecosystems are difficult to predict, but some studies have shown decoupling of important plant-pollinator and seed-dispersal relationships, and exotic species could benefit. Migratory birds driven by photoperiod are likely to arrive and attempt to breed at times of reduced food abundance since local plant productivity and prey are more attuned to temperature regimes that are shifting with respect to the calendar and likely to occur earlier compared to the birds' arrival. One possible impact is early leafout of Indiana's forests prior to the normal arrival of migratory species, leading to less effective predation by birds on forest insect pests.

The impacts of West Nile virus on bird populations are well documented, especially on crows and relatives (LaDeau et al. 2007), and presents a likely harbinger of future invasions of pathogens and disease vectors. The ability of bird populations to adapt to changing biological interactions will likely be slow in comparison with the rate of change in species' abundances. State threatened species, such as breeding populations of Sandhill cranes and upland sandpipers, in addition to Federally endangered species such as the piping plover, are likely to lose their already tenuous foothold in Indiana.

Summer drought and early spring runoff will contribute to the already extensive loss of Indiana wetlands, which provide habitat for migratory shorebirds and waterfowl, and 16 of 36 state-listed species of breeding birds. Wetland-associated birds provided a large portion of the outdoor recreation industry, including both hunting (estimated at \$2.3 billion nationally) and bird watching (estimated at \$32 billion nationally). Twenty-nine percent of Hoosiers identify themselves as bird watchers, placing Indiana 15<sup>th</sup> among the states in proportion of residents including themselves in this activity (La Rouse 2003).

### Mammals

Mammals in Indiana play a critical role in many ecosystem functions. Mammals influence forest regeneration and succession patterns both as primary dispersers for natural regeneration of tree species like oaks and also as herbivores altering recruitment patterns for tree seedlings as well as other native forest understory vegetation. It is unclear how quickly climate change patterns may alter the community dynamics of forest understory plants but it is safe to assume that the speed and magnitude of perturbations to those processes will be influenced by interactions with white-tailed deer whose densities have been demonstrated to profoundly impact ecological succession in Indiana's state parks (Webster et. al. 2001). Mammal species also contribute greatly to pest management in Indiana's agricultural fields (e.g. over a typical summer a colony of 150 big brown bats consume enough beetles to preclude the production of 33 million root worm larvae that feed on corn; Whitaker 1995). Changing cropping patterns in response to climate change may have unforeseen interactions with changing habitat availability for such wildlife species that perform economically valuable pest management functions. Shifting habitat availability related to climate change and associated alterations in human land use patterns will change the distribution of many mammalian species throughout the state of Indiana because these wild mammals depend upon vegetation that will be altered by climate change (Swihart et al. 1994). Such shifts in areas of activity may increase the rate of contact between species like raccoons and crops leading to increased economic losses through crop depredation. The potential concentration of wildlife species in closer proximity to humans and areas where humans are more active may also increase the risks of disease transmission to humans as well as livestock.

Other mammal species are valued by the citizens of Indiana for their unique characteristics and rarity in the state and the likely impacts of climate change upon these mammals are not simple to predict. An excellent example is the swamp rabbit which is Indiana's rarest mammal. A recent survey (Roy-Nielson et al. 2007) estimates that there are only 40 individual swamp rabbits present in the state of Indiana. Swamp rabbits are a highly prized game species in several neighboring states (Kentucky and Illinois) and climate change could lead to more habitat for swamp rabbits in southern Indiana. However warming temperatures associated with climate change may not be sufficient to enhance opportunities for the state's most endangered mammal because throughout their range swamp rabbits are associated with bottomland hardwood forest habitat types (Zollner et al. 2000) and land use practices in southern Indiana may preclude the expansion of these forest types even if climate change creates more opportunity for their creation. Thus we are left with a critical gap in our knowledge of swamp rabbit habitat requirements at the northern limits of the species range where climate change may present us with a chance to enhance the numbers of the state's most endangered mammal. More broadly, climate change will cause distributional shifts in the range of many threatened and endangered mammalian species and there is a real need to understand how human land uses may create barriers (e.g. highways) that populations of these valued wildlife species will not be able to cross without some human intervention such as mitigating structures in road designs. So climate changes necessitates a better understanding of how human land use patterns alter the connectivity of Indiana's landscape for mammalian wildlife species with a wide range of life history characteristics (e.g. varying degrees of vagility).

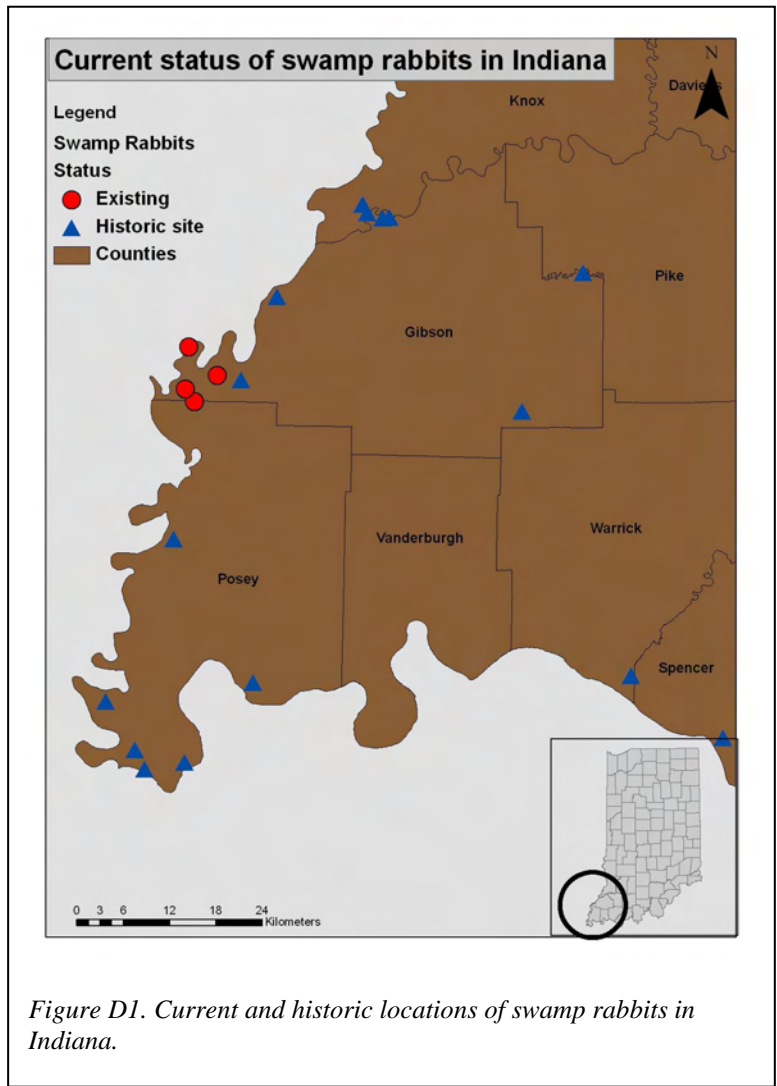


Figure D1. Current and historic locations of swamp rabbits in Indiana.

### Trees

An extensive analysis has been performed of tree species richness and forest types under five different climate change scenarios (Iverson and Prasad, 2001). In Indiana, all models predict a

dramatic reduction in forests that contain Black walnut, black cherry, maple and beech. All models predict a reduction of > 500 km<sup>2</sup> in the Eastern US, with much of that reduction in states including and surrounding Indiana. Part of this shift will move to oak forest types, but it is worth noting that much of this shift will not occur to high value commercial species. Thus if these climate change models are accurate, the Indiana forest products industry might incur additional transportation costs, be forced to offer different product lines with lower value hardwoods, or shift to areas where the economics are more favorable.

#### Grasses, Weeds and Native Plants

If future conditions point toward a warming trend, it is anticipated that many invasive exotic plant species might move northward in/into Indiana. These would include *Ailanthus*, kudzu, oriental bittersweet (although it already occurs commonly in the Dunes), privet, *Wisteria*, *Paulownia*, and Japanese stilt-grass. What impact such a trend might have on existing problematic exotics like Amur honeysuckle and garlic mustard is hard to predict, but since they seem to thrive in the northern part of the state and the Upper Midwest in general, increasing temperatures may work against these species.

If futures contain more extreme weather events, such as deepening/more extended drought, would certainly impact forest and grassland systems, perhaps favoring oak in some areas (possibly beneficial); in grasslands and prairie restorations, increased temperatures and more sporadic moisture may actually favor established prairie restoration areas (because of their drought tolerance compared to competitors), but will make establishment much more difficult and unpredictable.

Tallgrass prairies in Indiana are comprised of mixed C-3, C-4 plant communities. Climate change may alter the current balance of these species in two ways. C-3 plants have been predicted to increase with elevated CO<sub>2</sub> concentrations because they are CO<sub>2</sub> limited compared with C-4 plants whose photosynthetic pathway concentrates CO<sub>2</sub>. However, two grassland studies have shown that warming and elevated CO<sub>2</sub> can lead declines in C-3 plants, including invasive plant species compared to C-4 plants (Owensby et al. 1999, Ziska et al. 2004, Williams et al. 2007). Climate change has also been shown to reduce plant available nitrogen through elevated CO<sub>2</sub> (Williams et al. 2001, Zhang et al. 2005). C-4 plants have a higher nutrient use efficiencies than C-3 grasses, and reduced nitrogen availability has been shown to benefit C-4 plants over C-3 plants in tallgrass prairie (Bleier & Jackson 2007). Changes that increase the dominance of C-4 plant species would change the plant community structure and may change ecosystem function, such as nutrient cycling, and have specific consequences for wildlife habitat (nutritional quality of forage and habitat requirements). On the other hand, in cases where C-3 plants are non-native invasive species, this trend could benefit tallgrass prairie management and restoration. Caution should be taken, however, because photosynthetic pathways may not be definitive predictors of competitive outcomes (Dukes 2007).

Weeds are a major pest in agricultural and less intensively managed systems and billions of dollars are spent annually in the United States on weed management. Yield losses due to weeds result in additional billions lost, primarily to growers. Climate change will likely have four major impacts on weeds and weed management. First, land managers (growers, homeowners, natural resource managers) in Indiana may face new weed species as species currently limited to

southern U.S. migrate into the state. For example, kudzu is currently present on limited acreage in Indiana; warming temperatures might increase its distribution to the detriment of Indiana forests. Northerly shifts in the geographical range of some of our current weeds might offset the arrival of new species. However, at a minimum, land managers will have to develop new strategies to respond to changes in our weed communities. Second, climate change may increase competitiveness of some weeds, particularly C4 species which maximize growth at higher temperatures than C3 species like soybeans (Tungate et al. 2007). Third, climate change may further weaken plant communities damaged by current invaders, i.e. emerald ashborer, limiting the ability of natural communities to resist invasion. Weeds are opportunistic species that readily invade disturbed areas. More extreme weather events, extended drought, canopy gaps opened as mesic forests transition to more xeric species or to grasslands may increase the availability of disturbed habitat that can be colonized. Finally, current management practices may be less effective under current climate change scenarios forcing growers to adopt more costly and/or less environmentally benign practices. For example, changes in soil temperature and in weed morphology, physiology, and phenology may affect herbicide efficacy, in some cases requiring higher application rates (Patterson 1995; Bailey 2004; Ziska et al. 2004; Ziska and Goins 2006).

## **E. Likely Impacts of Climate Change on the Soils of Indiana**

*Cliff T. Johnston, Dept. of Agronomy*

The soils of Indiana are one its major natural resources. A disproportionately large fraction of our total economy is based on the health and quality of our soils. All aspects of Indiana agriculture are critically linked to the soil. In addition, we use soils to support the buildings we live and work in, and the roads we drive on, and to accept and purify many our waste products. Soil functions as a living filter where all of the water in our aquifers passes through the soils and all runoff entering our streams and lakes flows over and is impacted by soils.

Within the soil, the stabilization of carbon in the form of soil organic matter is essential in maintaining the productivity and sustainability of agricultural land. Loss of soil organic matter is positively correlated with increased soil loss, loss of soil structure, and an overall decrease in the soil's ability to retain moisture and essential nutrients for plant growth.

Based on projected increases in temperature and overall length of the growing season, agricultural productivity and crop growth would increase. Provided that a sufficient amount of crop residue is returned to the soil, soil organic matter would be preserved. However, 'hotter, drier summers' would lead to an overall loss of soil organic matter resulting from increased soil respiration, the biological breakdown of plant and animal residues in the soil into CO<sub>2</sub>. This combined with initiatives to capture more carbon from crops through cellulosic conversion of corn stover to ethanol would negatively impact soil carbon. These impacts will require new initiatives/strategies to maintain and preserve soil organic matter.

Although cultivated organic soils do not represent a large fraction of agricultural landscape (1.5 %), these soils are a dominant source term of carbon emissions. Based on a collaborative effort between the USDA Natural Resources Conservation Service and Colorado State University in "The Indiana Carbon Storage Project", greenhouse gas emission were modeled for Indiana based on the Century Model (Smith et al., 2002). Based on the data for 1999, our agricultural landscape consisted of 12.6 million acres in cropland, 0.6 million acres in CRP/Grass conservation, 0.06in tree/wetland conservation, and 0.2 million acres of cultivated organic soils. Based on the model parameters, a total of 1.3 million tons of carbon were sequestered in 12.7 million acres of cropland, or 0.1 ton of carbon stored/(acre-year). However, a total of 750,000 tons of carbon was lost from cultivated organic soils which represent only a small fraction of our agricultural landscape (1.5%). On a per acre basis, this corresponds to 3 tons of C lost/(acre-year). Thus, approximately half of the carbon being stored in 12.7 million acres is lost from 213,000 acres of cultivated organic soils. The loss of carbon from this small fraction of our agricultural landscape resulted from draining and cultivation of these soils. Exposure of these organic soils to oxygen (drainage and continued cultivation) and increased temperature will increase the loss of soil organic matter. In other words, taking these soils out of production and preserving their soil organic matter would not significantly impact Indiana agriculture. Policy changes to provide a mechanism where these soils are not drained and taken out of cultivation could significantly increase the overall amount of carbon being stored in Indiana soils.

## F. Possible Impacts of Climate Change on Indiana Human Health

Noah Diffenbaugh, Dept. of Earth and Atmospheric Sciences; Paul Shepson, Dept. of Earth and Atmospheric Sciences and Dept. of Chemistry

### Heat- and Cold-Related Health Effects

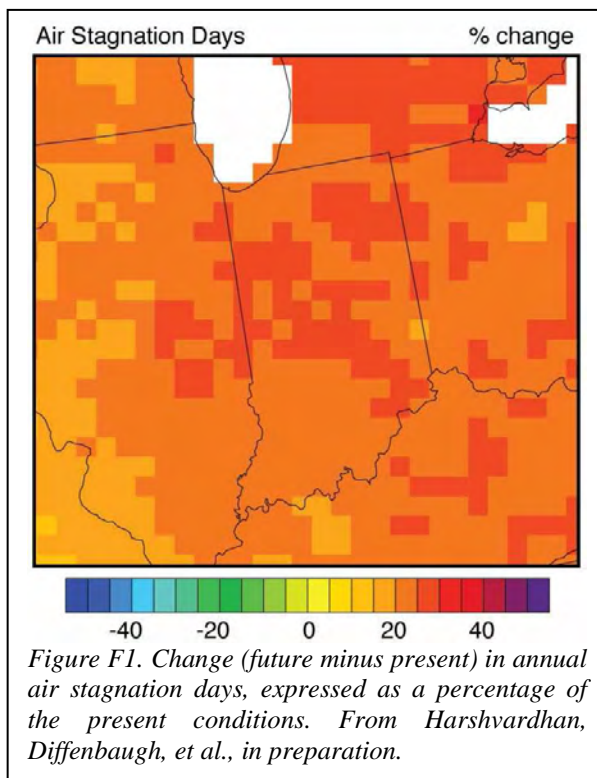
Heat stress poses a substantial threat to human health, particularly to those individuals that are already infirm (Rothfus 1990, Changnon et al. 1996, Poupadere et al. 2005). The effects of heat stress are most pronounced when exposure lasts for extended periods (e.g., (Poupadere et al. 2005)). The occurrence of extremely hot days is likely to increase in Indiana if greenhouse gas concentrations continue to rise unabated (e.g., (Meehl & Tebaldi 2004, Diffenbaugh et al. 2005) and figure above). Increases in the occurrence of extreme hot events – including more protracted periods of severe heat – would likely increase the risk of heat-related morbidity and mortality.

At present, weather-related winter mortality is greater than weather-related summer mortality (Kalkstein & Greene 1997). The frequency and magnitude of extreme cold events in Indiana is likely to be substantially reduced if greenhouse gas concentrations continue to rise unabated ((Diffenbaugh et al. 2005), and figure above). However, because winter weather-related mortality is less sensitive to changes in temperature, attempts to quantify future changes in heat- and cold-related mortality indicate that increases in summer mortality will outweigh decreases in winter mortality (Kalkstein & Greene 1997).

### Pollution-Related Health Effects

Air pollution illnesses of most concern/impact relate to ozone and particulate matter, both of which are regulated by the Clean Air Act (CAA). Interestingly, they are not emitted, but produced in the atmosphere from precursors that are emitted. Indiana occasionally violates the CAA standards, most often in the Indianapolis area and northwest corner of the state.

Meteorological conditions can support or inhibit the health risks of atmospheric constituents such as ozone and particulates. Thus, changes in those meteorological conditions induced by global warming could enhance or reduce the risk of atmospheric health risks. Of particular concern is the occurrence stagnant high-pressure air masses, as atmospheric stagnation can result in protracted exposure to pollutants, and exacerbates the development of photochemical smog events. Thus, we have calculated the occurrence of air stagnation conditions in the present and projected future climates. We find that elevated greenhouse gas concentrations induce changes in regional weather that increase the occurrence of stagnation events over Indiana up to 30% (see Figure F1). Increases in air stagnation events could increase the risk of pollution-related illness.



However, future changes in pollution-related morbidity and mortality will be dictated not only by changes in meteorological conditions, but also by changes in pollution emissions and atmospheric chemistry. This is borne out by several recent coupled climate-chemistry models (Tagaris et al., 2007; Wu et al., 2008). The Tagaris et al. (2007) study indicates that for the midwest, changes in emissions will have a significantly greater impact on ozone and particulate matter than will the climate change impact. While climate change impacts will increase summertime average ground level ozone by only 1-3 ppb (or about 2-6% in summer; Wu et al., 2008), there will be a greater incidence of smog episodes. In other words, climate change increases the frequency of pollution events that impact human health, in part due to incidences of stagnation events.

Perhaps most significantly, Wu et al. (2008) discuss the “climate change penalty” related to management of ground level ozone; this penalty for Indiana is only a few ppb, on average. But climate change increases the frequency of events, and the events are what matter in terms of human health and the CAA regulations. Thus, in tangible terms, it will take a further reduction of NO<sub>x</sub> emissions (from combustion sources) of ~25% in 2050, to meet the same CAA standard, due to the “climate change penalty”.

Impacts on particulate matter are less well understood. For Indiana in summer time, much of the fine particulate matter (“PM2.5”) is derived from SO<sub>2</sub> emitted from coal-fired power plants. Thus it is likely that particulate matter in the future will be most sensitive to changes in the base electric power load, and how that load is managed. We note, however, that that is sensitive to climate change, and to summer time stagnation events. In Indiana in summer, a significant fraction of particulate matter derives from volatile organic compounds (VOCs), much of which is emitted by vegetation. These emissions increase exponentially with increasing temperature. Secondary organic aerosol (“SOA”) derived from VOCs can be important in Indiana, especially when the wind direction is from forested regions to the south and southwest. This is an area of intensive research, as it is not very well understood (Liao et al., 2007; Dawson et al., 2007).

### *Infectious Diseases*

The potential effect of future climate change on infectious diseases in Indiana is a topic of current research, including at Purdue University. Of particular interest is the possible introduction of exotic vector-borne diseases. Temperature is likely to influence vector-borne viruses in at least three ways. First, warmer temperatures can increase viral replication, which could increase disease prevalence (Kilpatrick, Diffenbaugh, et al. in prep). Second, cold temperatures can control the length of the viral transmission season (Kilpatrick, Diffenbaugh, et al. in prep), meaning that decreases in severe cold events could increase disease prevalence. Third, high temperatures can decrease mosquito survivorship (Kilpatrick, Diffenbaugh, et al. in prep), meaning that projected increases in the occurrence of extreme hot events could decrease disease prevalence. How these three influences will interact in a substantially warmer climate is currently unknown. Further, how changes in vector ecology will affect disease transmission is also unknown. In particular, humidity and precipitation been shown to influence vector ecology (Shaman et al. 2002). This influence indicates that changes in the hydrologic cycle could also influence vector-borne disease prevalence in Indiana, although whether those hydrologic changes will enhance or inhibit disease prevalence remains uncertain.

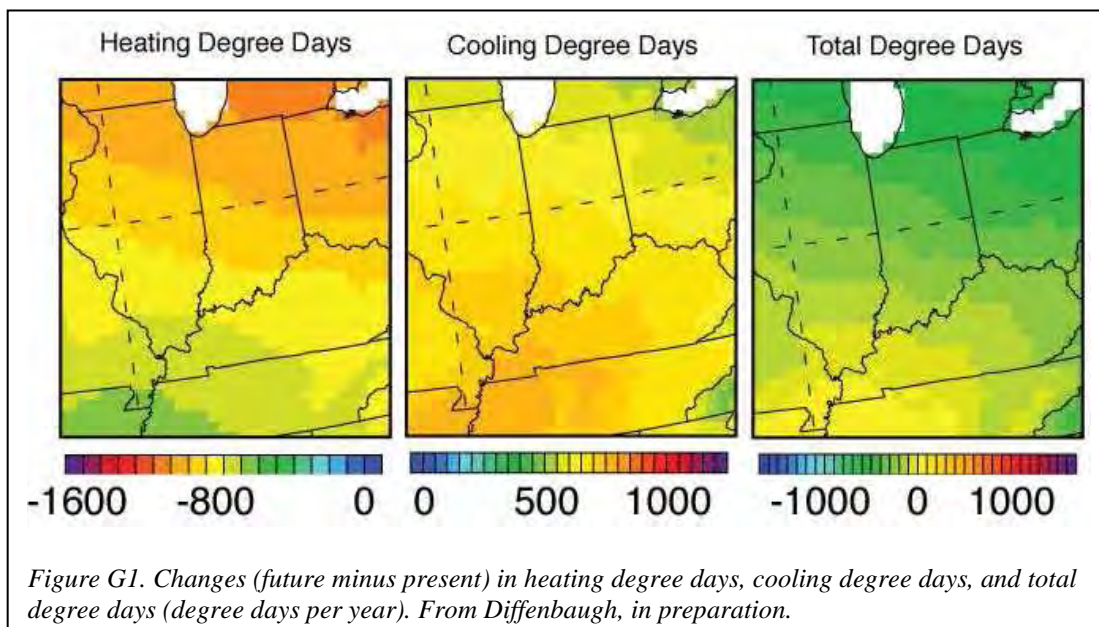


## G. Possible Impacts of Climate Change on Indiana Heating and Cooling Demand

Noah Diffenbaugh, Dept. of Earth and Atmospheric Sciences; Kevin Gurney, Dept. of Earth and Atmospheric Sciences and Dept. of Agronomy

As a first approximation, warmer conditions are likely to increase demand for cooling and increase demand for heating. One source of uncertainty is where in the United States increased cooling demand will dominate, and where decreased heating demand will dominate. We have calculated total meteorological heating and cooling demand for the United States, using the base 65 °F method used by NOAA, and scaling for population density. In Indiana, heating demand decreases by up to -1000 degree days, while cooling demand increases by up to 700 degree days (see figure below). Total demand decreases throughout Indiana in the future climate, with peak decreases of 500 degree days occurring in northeast Indiana (see Figure G1).

It is important to consider that a different mixes of fuels and energy generation technology are used for heating and cooling. Thus, quantification of how these changes in demand will influence actual energy usage and emissions requires further analysis.



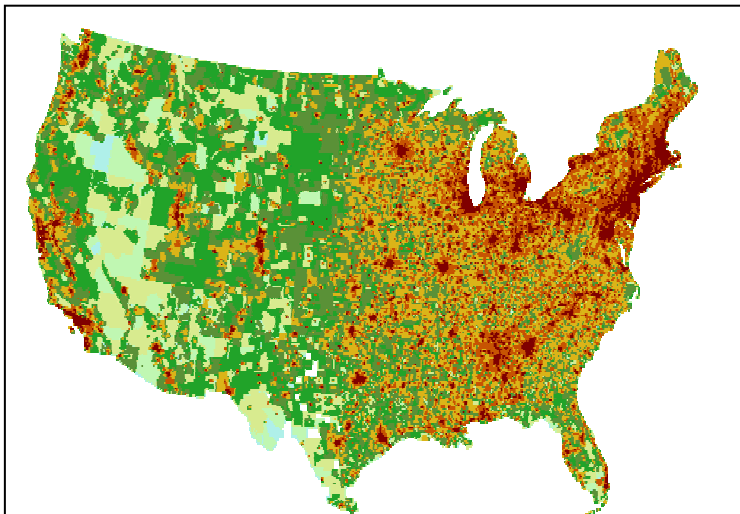
## H. Carbon management opportunities and consequences

*Kevin Gurney, Dept. of Earth and Atmospheric Sciences and Dept. of Agronomy; Qianlai Zhuang, Dept. of Earth and Atmospheric Sciences and Dept. of Agronomy; Noah Diffenbaugh, Dept. of Earth and Atmospheric Sciences*

### Inventory/Registry

The Lieberman-Warner bill discusses a greenhouse gas registry system that will be constructed by the EPA Administrator to assist in quantifying baselines of emissions and progress toward the emission reduction goals described in the bill (Title I, subtitle A). Relevant to this proposal is current research underway at Purdue University in the state of Indiana. Funded by a combination of NASA and DOE, a comprehensive US inventory of fossil fuel carbon dioxide is near completion and quantifies these emissions from every source in the United States at sub-county resolution every hour (see Figure H1).

These emissions include all economic sectors and quantifies these emissions down to the individual industrial facility and individual roadway. The importance of this work to the State of Indiana and the operationalization of the Lieberman-Warner bill may be worthy of consideration by the Indiana delegation (see Figure H2). This work should be highlighted and may save the EPA Administrator considerable effort and cost. At the least, this work should form a crucial element of the Registry construction.



*Figure H1. Total US fossil fuel CO<sub>2</sub> emissions (tonnes C/year) produced by the Vulcan Project for the year 2002. Resolution: 10 km/hourly.*



*Figure H2. Contribution of the residential sector to fossil fuel CO<sub>2</sub> (tonnes C/year) emissions in the state of Indiana. Resolution: 10 km/hourly.*

### Agriculture and Forestry Offsets

The Lieberman-Warner bill includes a fairly extensive mechanism of agriculture and forestry emissions offsets that emitters can use in place of, or as an amendment to, greenhouse gas emission reductions (Title II, Subtitle D). This component of the Lieberman-Warner bill has

wide-ranging implications for the State of Indiana as there are a variety of offset opportunities in the agriculture sector, some of which have already been practiced in the state. In addition to the potential to accrue offset credits, there are potentially negative implications to some of these activities having to do with climate feedbacks and implications for other environmental attributes that might be considered unintended consequences of offset activities.

The best and probably most familiar technique available to the agricultural sector of Indiana to accrue offsets is through the use of reduced or no tillage agriculture, use of fallow periods, and conversion of marginal agricultural land to grassland or forest. Recent estimates indicate that the agricultural lands of the state are currently a net sink of atmospheric CO<sub>2</sub> of roughly 0.8 million tons of carbon/year (estimate for the year 1999; Smith et al., 2002). Since more than one-half of Indiana's 5.1 million hectares of cropland are still managed using conventional tillage practices, considerable potential remains. It must be noted for context that this amount of sequestration constitutes roughly 2% of Indiana's 1999 fossil fuel carbon emissions.

Similarly important for Indiana are offsets that accrue from manure management and disposal which include waste aeration and methane capture and combustion. Given the large amount of hog farming within the state, these mechanisms to lower the methane emissions could lead to significant offsets.

Though small in overall state context, there are a few additional allowed offsets that are relevant to Indiana. These include afforestation, reforestation, and forest management practices. Though much smaller in extent, forest lands or land with near-term potential for afforestation and reforestation, sequester much larger amounts of carbon per unit area than do agricultural lands.

These practices also generate additional risks and benefits, depending upon extent, intensity and criteria employed. Efforts at reforestation and afforestation often impart significant co-benefits such as improved or additional habitat for wildlife, soil and water retention, aesthetic improvements, and microclimate changes. Certainly practices associated with carbon sequestration in cropland most directly influence soil organic matter, a considerable co-benefit of sequestration.

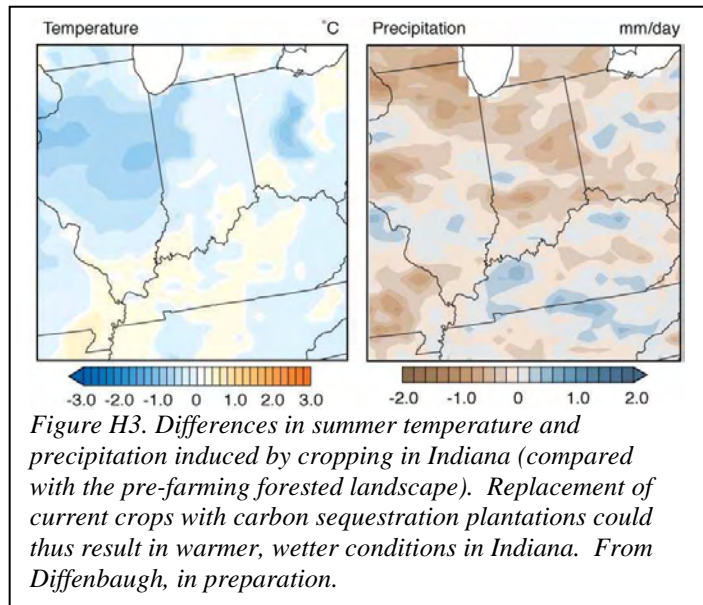
For Indiana, the likelihood that significant additional carbon sequestration in cropland will occur is fundamentally tied to the opportunity cost of cropland. This opportunity cost is currently undergoing potential changes, driven in large measure, by the opportunity to grow corn for an emerging biofuel market. To the extent that co-benefits and risks are quantified in market terms, sequestration may or may not increase in competitive advantage with the cropland opportunity cost.

### *Physical Climate Changes*

It is now well established that land cover influences surface climate, both through surface energy balance and through biogeochemical cycles (Pielke et al. 2002). Changes in land cover resulting from both direct human modification and biogeographic change could thus have substantial impact on surface climate in the coming decades (Douville et al. 2000, Levis et al. 2000, Bergengren et al. 2001, Diffenbaugh 2005b, Diffenbaugh 2005a, Feddema et al. 2005). We have

quantified the contribution of modern land cover to surface climate in the United States. In Indiana, the modern land cover results in cooler, drier conditions than would occur with the pre-farming land cover (see Figure H3). These results indicate that replacement of current crops with carbon sequestration plantations could thus result in warmer, wetter conditions in Indiana.

Although the result of crop-induced cooling is consistent with most other experiments in the peer-reviewed literature (e.g., (Bonan 1999)), further experiments testing the effects of land cover change in Indiana alone are required.



## I. References

- Bergengren JC, Thompson SL, Pollard D, DeConto RM (2001) Modeling global climate-vegetation interactions in a doubled CO<sub>2</sub> world. *Climatic Change* 50:31-75
- Bleier JS, Jackson RD (2007) Manipulating the quantity, quality, and manner of C addition to reduce soil inorganic N and increase C<sub>4</sub> : C<sub>3</sub> grass biomass. *Restoration Ecology* 15:688-695
- Bailey SW (2004) Climate change and decreasing herbicide performance. *Pest Management Science* 60:158-162
- Bleier JS, and Jackson RD (2007) Manipulating the quantity, quality, and manner of C addition to reduce soil inorganic N and increase C<sub>4</sub> : C<sub>3</sub> grass biomass. *Restoration Ecology* 15:688-695
- Bogan AE (1993) Freshwater bivalve extinctions (Mollusca: Unionoida): a search for causes. *American Zoologist* 33:599–609
- Bonan GB (1999) Frost followed the plow: Impacts of deforestation on the climate of the United States. *Ecological Applications* 9:1305-1315
- Changnon SA, Kunkel KE, Reinke BC (1996) Impacts and responses to the 1995 heat wave: A call to action. *Bulletin Of The American Meteorological Society* 77:1497-1506
- Diffenbaugh NS (2005a) Atmosphere-land cover feedbacks alter the response of surface temperature to CO<sub>2</sub> forcing in the western United States. *Climate Dynamics* 24:237-251
- Diffenbaugh NS (2005b) Sensitivity of extreme climate events to CO<sub>2</sub>-induced biophysical atmosphere-vegetation feedbacks in the western United States. *Geophysical Research Letters* 32:L07702, doi:07710.01029/02004GL022184
- Diffenbaugh NS, Pal JS, Giorgi F, Gao X (2007) Heat stress intensification in the Mediterranean climate change hotspot. *Geophysical Research Letters* 34:L11706, doi:11710.11029/12007GL030000
- Diffenbaugh NS, Pal JS, Trapp RJ, Giorgi F (2005) Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of Sciences of the United States of America* 102:15774-15778
- Doering OC, Randolph JC, Southworth J., and Pfeiffer RA (Eds.). 2003. *Effects of Climate Change and Variability on Agricultural Production Systems*. Kluwer Academic Publishers, Norwell, MA
- Douville H, Planton S, Royer JF, Stephenson DB, Tyteca S, Kergoat L, Lafont S, Betts RA (2000) Importance of vegetation feedbacks in doubled-CO<sub>2</sub> climate experiments. *Journal of Geophysical Research-Atmospheres* 105:14841-14861
- Dukes JS (2007) Tomorrow's plant communities: different, but how? *New Phytologist* 176:235-237
- Feddema JJ, Oleson KW, Bonan GB, Mearns LO, Buja LE, Meehl GA, Washington WM (2005) The importance of land-cover change in simulating future climates. *Science* 310:1674-1678
- Gibson CA, Meyer JL, Poff NL, Hay LE, and Georgakakos A (2005) Flow regime alterations under changing climate in two river basins: implications for freshwater ecosystems. *River Research and Applications* 21: 849-864
- Hamilton JG, Dermody O, Aldea M, Zangerl AR, Rogers A, Berenbaum MR, and Delucia EH (2005) Anthropogenic changes in tropospheric composition increase susceptibility of soybean to insect herbivory. *Environmental Entomology* 34: 479-485

- Iverson LR and Prasad AM (2001) Potential changes in tree species richness and forest community types following climate change. *Ecosystems* 4, 3:186-199
- Kalkstein LS, Greene JS (1997) An evaluation of climate/mortality relationships in large US cities and the possible impacts of a climate change. *Environmental Health Perspectives* 105:84-93
- Kling GW, Hayhoe K, Johnson LB, Magnuson JJ, Polasky S, Robinson SK, Shuter BJ, Wander MM, Wuebbles DJ, Zak DR (eds) (2003) *Confronting Climate Change in the Great Lakes Region: Impacts on Our Communities and Ecosystems*, Vol. UCS Publications, Cambridge, MA
- LaDeau SL, Kilpatrick AM, Marra PP. (2007) West Nile virus emergence and large-scale declines of North American bird populations. *Nature* 447: 710-713
- La Rouché GP (2003) *Birding in the United States: a demographic and economic analysis*. GP USFWS Report 2001-1
- Levis S, Foley JA, Pollard D (2000) Large-scale vegetation feedbacks on a doubled CO<sub>2</sub> climate. *Journal of Climate* 13:1313-1325
- McMahon RJ (1991) Mollusca: Bivalvia. *Ecology of freshwater mussels of the United States and Canada*. *Fisheries* 18:6-22
- Meehl GA, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. *Science* 305:994-997
- Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in stream-flow and water availability in a changing climate. *Nature* 438:347-350
- Owensby CE, Ham JM, Knapp AK, Auen LM (1999) Biomass production and species composition change in a tallgrass prairie ecosystem after long-term exposure to elevated atmospheric CO<sub>2</sub>. *Global Change Biology* 5:497-506
- Paine RT, Tegner MJ, and Johnson EA (1998) Compounded perturbations yield ecological surprises. *Ecosystems* 1: 535-545
- Parmesan C, and Yohe GA (2003) Globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421: 37-42
- Parmesan C (2006) Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology Evolution and Systematics* 37: 637-669
- Patterson DT (1995) Weeds in a changing climate. *Weed Science* 43: 685-701
- Pielke RA, Marland G, Betts RA, Chase TN, Eastman JL, Niles JO, Niyogi DDS, Running SW (2002) The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences* 360:1705-1719
- Poumadere M, Mays C, Le Mer S, Blong R (2005) The 2003 heat wave in France: Dangerous climate change here and now. *Risk Analysis* 25:1483-1494
- Rothfus LP (1990) The heat index equation (or, more than you ever wanted to know about heat index). NWS Southern Region Technical Attachment, SR/SSD 90-23
- Shaman J, Stieglitz M, Stark C, Le Blancq S, Cane M (2002) Using a dynamic hydrology model to predict mosquito abundances in flood and swamp water. *Emerging Infectious Diseases* 8:6-13
- Sinha T and Cherkauer KA (2006) Time series analysis of soil freeze thaw processes in Indiana, ASA-CSSA-SSSA International Meeting, Indianapolis, IN, November 12-16, Abstract

- 318-3. Wuebbles, D. and K Hayhoe (to be released 2008), *Climate Change and Chicago: Projections and Potential Impacts*
- Smith P, Brenner J, Paustian K, Bluhm G, Cipra J, Easter M, Elliott ET, Killian K, Lamm D, Schuler J, and Williams S (2002) Quantifying the change in greenhouse gas emissions due to natural resource conservation practice application in Indiana. Final report to the Indiana Conservation Partnership. Colorado State University Natural Resource Ecology Laboratory and USDA Natural Resources Conservation Service, Fort Collins, CO, USA
- Trapp RJ, Diffenbaugh NS, Brooks HE, Baldwin ME, Robinson ED, Pal JS (2007) Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proceedings of the National Academy of Sciences* 104:19719-19723
- Tungate KD, Israel DW, Watson DM, and Ruffy TW (2007) Potential changes in weed competitiveness in an agroecological system with elevated temperatures. *Environmental and Experimental Biology* 60: 42-49
- USBC (1998) *Statistical Abstract of the United States 1996*. 200th ed. Washington, DC: U.S. Bureau of the Census, U.S. Government Printing Office
- White MA, Diffenbaugh NS, Jones GV, Pal JS, Giorgi F (2006) Extreme heat reduces and shifts United States premium wine production in the 21st century. *Proceedings of the National Academy of Sciences* 103:11217-11222
- Williams AL, Wills KE, Janes JK, Schoor JKV, Newton PCD, Hovenden MJ (2007) Warming and free-air CO<sub>2</sub> enrichment alter demographics in four co-occurring grassland species. *New Phytologist* 176:365-374
- Williams JD, Warren ML, Cummings KC, Harris JL, and Neves RJ (1993) *Conservation status and classification of freshwater invertebrates*. Academic Press, San Diego, California.
- Williams JW, Jackson ST, and Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proceedings of the National Academy of Sciences* 104:5738-5742
- Williams MA, Rice CW, Owensby CE (2001) Nitrogen competition in a tallgrass prairie ecosystem exposed to elevated carbon dioxide. *Soil Science Society of America Journal* 65:340-346
- Zhang W, Parker KM, Luo Y, Wan S, Wallace LL, Hu S (2005) Soil microbial responses to experimental warming and clipping in a tallgrass prairie. *Global Change Biology* 11:266-277
- Ziska LH, Faulkner S, Lydon J (2004) Changes in biomass and root: shoot ratio of field-grown Canada thistle (*Cirsium arvense*), a noxious, invasive weed, with elevated CO<sub>2</sub>: implications for control with glyphosate. *Weed Science* 52:584-588