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Climate change impacts on terrestrial ecosystems in metropolitan Chicago and its surrounding, multi-state region

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ABSTRACT

This paper describes the potential impacts of warming temperatures and changing precipitation on plants, wildlife, invasive species, pests, and agricultural ecosystems across the multi-state region centered on Chicago, Illinois. We examine a geographic area that captures much of Lake Michigan, including a complex mosaic of urbanization and agriculture surrounding southern Lake Michigan. We consider species currently present within this broad region as well as species that are expected to move into or out of the area as climate zones shift northward through the coming century. Our analysis draws upon disparate data sources to compile projections. We conclude that a complex mixture of land use poses particular challenges to natural ecosystems in this region under climate change. Dispersal is likely to be limited for some species, and some populations of native taxa may already be reduced due to habitat loss. Other species can persist, even thrive, within a mixed landscape mosaic, provided natural areas and green spaces are available. If such spaces are somehow connected, they can provide opportunities for native species to inhabit and move through the metropolitan region (perhaps even better than the landscapes previously dominated by agriculture). Strategies for adapting regional agriculture and minimizing pest outbreaks also call for creative management intervention. With additional research, Chicago and its surrounding environs have an opportunity to provide leadership on effective management of natural resources under climate change.

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Introduction

The greater Chicago area – defined here as the broad geographic region surrounding Lake Michigan containing portions of Michigan, Indiana, Illinois, and Wisconsin – lies within a mid-continental forest-grassland transition zone characterized by rich soils and mosaics of forest, savanna, grassland, and wetland ecosystems (Olson et al., 2001). Although these ecosystem types remain in the region, they have been highly modified during the past two centuries to support mechanized agriculture and to accommodate urban and suburban development. For example, over all of Illinois, less than 12,000 acres of forest and less than 3,000 acres of prairie remain in relatively undisturbed conditions; conversion rates during the last half of the 19th century rivaled or outpaced any tropical deforestation rates underway in recent decades (Iverson, 1988, 1991).

Many plant and animal species characteristic of the region's original ecosystems occur in these modified ecosystems, although often at levels much reduced from pre-development levels, and with many introduced species interspersed among the natives (Iverson, 1991). Native plant diversity is especially rich in lesser-disturbed areas within forest preserves, parks, public and private natural areas, riverine habitats, roadside rights of way, utility corridors, and residential lots (Swink and Wilhem, 2002). They are valued for aesthetic reasons (e.g., large, pre-settlement bur, red and white oak trees, *Quercus* spp.) and for the ecological services they provide, including provision of wildlife habitat, modification of microclimate (shade and windbreaks), and regulation of water, sediment, and nutrient releases to rivers and lakes. Many native birds, mammals, reptiles, amphibians, fishes, and insects remain within the region, either occupying remnants of original ecosystems or inhabiting modified ecosystems (e.g., see Panzer et al., 1995). Some have been extirpated from the region (black bear (*Ursus americanus*) for example) or have become extinct (passenger pigeon (*Ectopistes migratorius*), while others such as white-tailed deer (*Odocoileus virginianus*) and raccoons (*Procyon lotor*) have increased. Some now common animals, like the house finch (*Carpodacus mexicanus*), are relatively recent arrivals.

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Changes in the region's ecosystems thus far have resulted primarily from land use conversion (from prairies, woodlands, forests, and wetlands to farms, cities, and suburbs), species introductions (intentional and accidental), and fire suppression in native prairies and savanna. For instance, in Illinois, the total number of vascular plant taxa recorded is 3208, of which 899 (23%) have been introduced (Iverson et al., 1997). Changes in temperature and precipitation resulting from increasing greenhouse gas emissions, however, are significantly altering plant growing conditions and thus the habitats that support wildlife and ecosystem services. Growing seasons in this area, similar to patterns across the Northern Hemisphere, have advanced by 1 to 1½ days per decade during the past 50 years (Schwartz et al., 2006). The extent to which climate alters the composition and functioning of the region's ecosystems will vary according to the different emission scenarios (e.g., see Hayhoe et al., 2010). In addition, ecosystems will be influenced by management decisions and land use choices and by the interactions of these factors with climate change. This paper is intended to affect the later by compiling information and projections for one of the country's most important urban and agricultural centers.

This paper examines species, or the habitats that they occupy, that are likely to either decline or arrive in the broad region centered on Chicago, Illinois, and explores potential risks of regional climate change for invasive species, pests, and agriculture. We then use these projections to recommend actions that reduce negative effects of climate change in the region. Data are compiled from diverse sources and therefore the study region varies slightly for various species below. In each case, analyses consider a sufficiently large scale to enable regional conservation planning.

Climate impacts on vegetation

As regional temperature warms, plant hardiness zones, a metric defined using average annual minimum temperatures (AMT) that determines what plant species can be cultivated in a region, are projected to move northward. Within the next few decades, the geographic region near the southwestern Lake Michigan will shift from its current USDA Plant Hardiness Zone designation of 5b, in which AMT ranges from −23 to −26 °C, upwards to 6a, with AMT ranging from −20.5 to −23 °C. This shift is irrespective of future emissions scenario (Table 1). By mid-century, plant hardiness is projected to remain at zone 6a under lower emissions and to shift further to zone 6b (AMT = −18 to −20.5 °C) under higher emissions. By the end of the century, the projected hardiness zones could shift to 6b under lower and to 7a (AMT = −15 to −18 °C) under higher emission scenarios. The projected shifts for mid- and late-century under the lower emission scenario would make conditions in the region equivalent to present hardiness zones in southern Illinois. Under the higher emission scenario, plant hardiness zones are projected to be similar to those of western Kentucky by mid-century and to northern Alabama by the end of the century.

Projected shifts in plant hardiness zones, as well as decreases in growing season moisture due to warmer, dryer summers, will have implications for the nearly 100 tree species and the larger numbers of shrubby and herbaceous species currently found in the multi-state area around Chicago. Some dominant species are likely to have their current boundaries migrate northward or will otherwise decline in abundance. Some less important species, and some species presently found further to the south, will assume greater importance. Projections by Iverson and colleagues (Iverson et al., 2008; Prasad et al., 2007) suggest that suitable habitats of important species such as northern red oak (*Quercus rubra*), black cherry (*Prunus serotina*), white oak (*Quercus alba*), sugar maple (*Acer saccharum*), and red maple (*Acer* rubrum) will decline substantially but will probably not disappear altogether. These projections were based on simulations using 38 predictor variables, including climatic variables. Values for future climate were drawn from the average of three global climate models under a higher (A1fi) and a lower (B1) emission scenario that were statistically downscaled to the U.S. Great Lakes region (described in Hayhoe et al., 2010). These models project, for example, dramatic declines in red oak habitat through time under either the lower or higher emission scenario (Fig. 1; Iverson et al. 2008).

Habitats of less common species, such as paper birch (*Betula papyrifera*), black ash (*Fraxinus nigra*), quaking aspen (*Populus tremuloides*), big-toothed aspen (*Populus grandidentata*), butternut (*Juglans cinerea*), balsam fir (*Abies balsamea*), black spruce (*Picea mariana*), and eastern hemlock (*Tsuga Canadensis*), could become rare or disappear altogether. Habitats for certain species which are now present, such as silver maple (*Acer saccharinum*), bur oak (*Quercus macrocarpa*), post oak (*Quercus stellata*), sweetgum (*Liquidambar styraciflua*), Kentucky coffee tree (*Gymnocladus dioicus*), black hickory (*Carya texana*), and wild plum (*Prunus americana*), could become more abundant as climate warms. Oak species that are now uncommon or absent from the region, such as southern red oak (*Quercus falcate*), Shumard oak (*Quercus shumardii*), and blackjack oak (*Quercus marilandica*), could extend their ranges northward into the area near Lake Michigan, especially if managers were to assist in their migration (McLachlan et al., 2007). Such efforts by planners would have the effect of maintaining oak forests and savannas though the proportions and overall composition of oak species occupying these ecosystems might change. For example, projections suggest that conditions for shortleaf pine (*Pinus echinata*) (Fig. 2), loblolly pine (*Pinus taeda*), water locust (*Gleditsia aquatica*), water oak (*Quercus nigra*), willow oak (*Quercus phellos*), and cedar elm (*Ulmus crassifolia*) are likely to increase in the region. However, it is not likely that this latter group of more southern species would migrate into the region during the next century without active management and planting (Iverson et al., 2004a,b).

The degree to which the habitats and abundances of tree species change through the century will differ in relation to rates of greenhouse gas emissions. Although the relative abundances of individual species will change due to climate change, consideration of general forest types is useful for management purposes. For example, using species associated with forest habitat types and the tree species projections as described above, a recent study suggested that climate favoring dominance of spruce-fir, aspen-birch, or white/red/jack pine forest types would be largely eliminated under a high and low emission scenario in the region near Lake Michigan (Fig. 3; Iverson et al., 2008). The maple-beech-birch forest habitat could remain relatively stable under lower emissions but could largely be replaced by oak-hickory under higher emissions (data not shown; see Iverson et al., 2008). Final outcomes of species compositions will largely be determined by many other abiotic and biotic factors influencing the ecosystem in concert with the changes in climate. Overall, species declines and losses, and increases in abundances of more heat and drought-tolerant species will likely be less pronounced under lower emissions which result in a more gradual rate of climate change.

The tree species present in ecosystems of the region will also be altered by plant pests and diseases. Some, such as emerald ash borer

Table 1
Plant hardiness zone changes for the multi-state region surrounding Chicago, Illinois, USA.

	Lower emissions		Higher emissions	
	PHZ zone	…similar to	PHZ zone	…similar to
1961–1990	5b	Chicago	5b	Chicago
2010–2039	6a	Central IL	6a	Central IL
2040–2069	6a	Southern IL	6b	Western KY
2070–2099	6b	Southern IL	7a	Northern AL

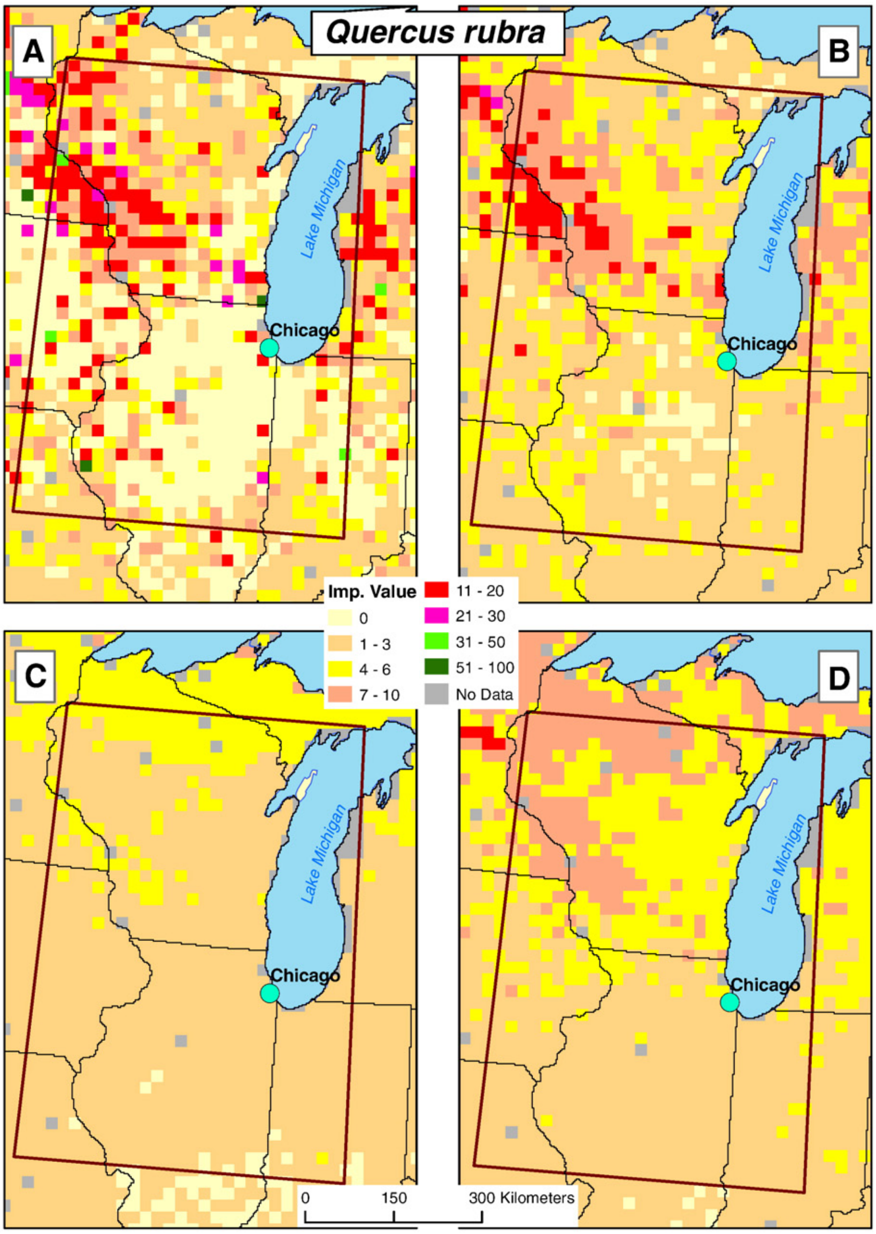

Fig. 1. Maps of suitable habitat for northern red oak (*Quercus rubra*) as measured (A), modeled under current conditions (B), and modeled under higher (C) and lower emission (D) scenarios in 2100. Importance values indicate the relative importance of the species based on both how dense the trees are as well as how large they are, as determined by the U.S. Forest Service Forest Inventory and Analysis units. The higher the number, the more abundant and/or large the species is. Redrawn from a larger geographic analysis in Iverson et al. (2008). Box indicates study area.

(Poland and McCullough, 2006), beech bark disease, maple decline, and oak wilt may combine with habitat loss to further decrease the populations of currently important species in the region's forests and residential areas. Susceptibilities of mature trees to pests and pathogens, and the activities of pests themselves, may increase with temperatures and growing season length (Dale et al., 2001).

In addition to forests, prairies and savannas were major components of the pre-19th Century landscape around Lake Michigan, particularly in the south. Conservation efforts in this region are often directed at maintaining remnants of these ecosystem types or at restoring them on degraded or abandoned lands. These ecosystems are composed of species favored under dry summers and periodic burning. As with forests, these ecosystem types can likely be maintained into the future under active management, even though some characteristic plant species may decline while other less abundant species might increase and be augmented by more drought and heat-adapted species from the south and west. Overall, grasslands and savannas are also valuable in maintaining habitat for indigenous and other valued plant and animal species. Areas occupied by marshes, riverine wetlands, and swamps have diminished greatly due to draining, channelizing of streams, and land use change. These ecosystem types may decline further due to more prolonged dry seasons and warmer summers, and to lowering of water tables.

Climate impacts on animals

In addition to plants, changing climate is expected to affect the abundance and distribution of animals in the region, including birds, insects, and mammals. The responses of these species will depend on the climatic tolerances of the animals themselves and on the responses of key species with which they interact. Specialist species that depend heavily on a particular resource, a mutualistic

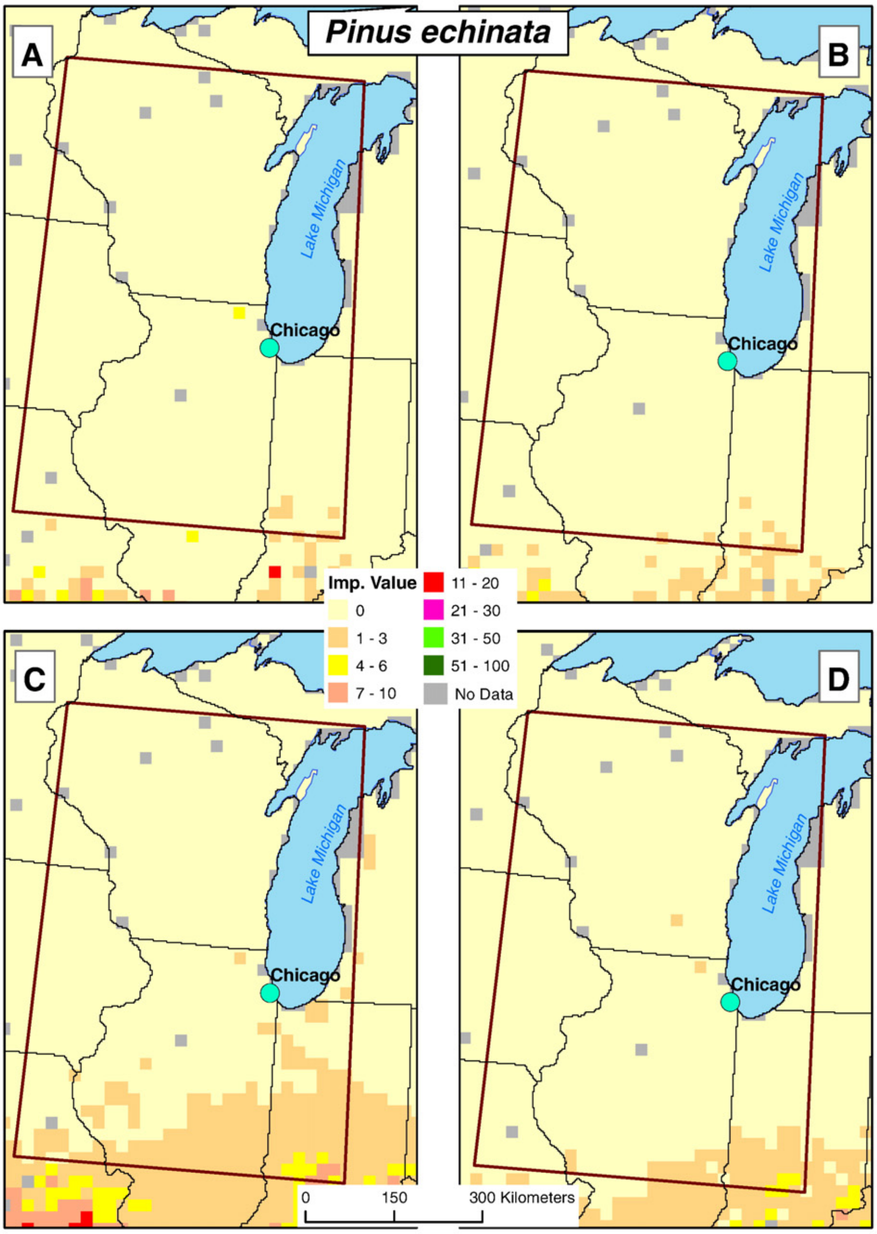

Fig. 2. Maps of suitable habitat for shortleaf pine (*Pinus echinata*) as measured (A), modeled under current conditions (B), and modeled under higher (C) and lower emission (D) scenarios in 2100. See description for Fig. 1. Redrawn from a larger geographic analysis in Iverson et al. (2008). Box indicates study area.

relationship, or a particular habitat will be affected both directly and indirectly by climate change.

Climate change will alter the timing of animal processes. A record of 55 different seasonal events (e.g., arrival dates of migratory birds) begun by Aldo Leopold in Sauk County, Wisconsin, indicates that 19 of these processes have occurred steadily earlier in the region over the last ~65 years (Bradley et al., 1999). Changes in the timing of plant processes also will affect animals if a shift involves a limiting factor in animal population growth or increases animal mortality. For example, changes in leaf chemistry brought on by elevated concentrations of CO_2 or by warmer temperature can change the timing of leaf flush, affecting the concentration of secondary chemicals that limit the growth of outbreaking insects such as gypsy moth (Lindroth and Kinney, 1998; Kinney and Knowlton, 1998; Ayres and Lombardero, 2000; Watt and McFarlane, 2002). Changes in the timing of bird migration relative to the timing of their food resources also have been shown to affect the reproductive success of pied flycatchers in Europe (Both et al., 2006). Changes in the abundance of animals due to changes in plants will require new or more intensive strategies of forest management in the case of outbreaking or invasive species (e.g., greater monitoring and treatment for pest control) and greater conservation efforts in the case of declining species (e.g., seeding or tending plant resources). Vulnerable or threatened species that occupy marginal habitats or utilize marginal plant resources may be particularly affected by changes in the timing and quality of their food plants.

The current distribution of suitable habitat for 147 common bird species in the eastern United States has been previously modeled using Breeding Bird Survey observations for the period 1981–1990, weather data, and associated tree species importance (Matthews et al., 2004, 2007). We then used as input data for future projections the average of three global climate models under a higher (A1fi) and a lower (B1) emission scenario that were statistically downscaled to the U.S. Great Lakes region (described in Hayhoe et al., 2010 and above for

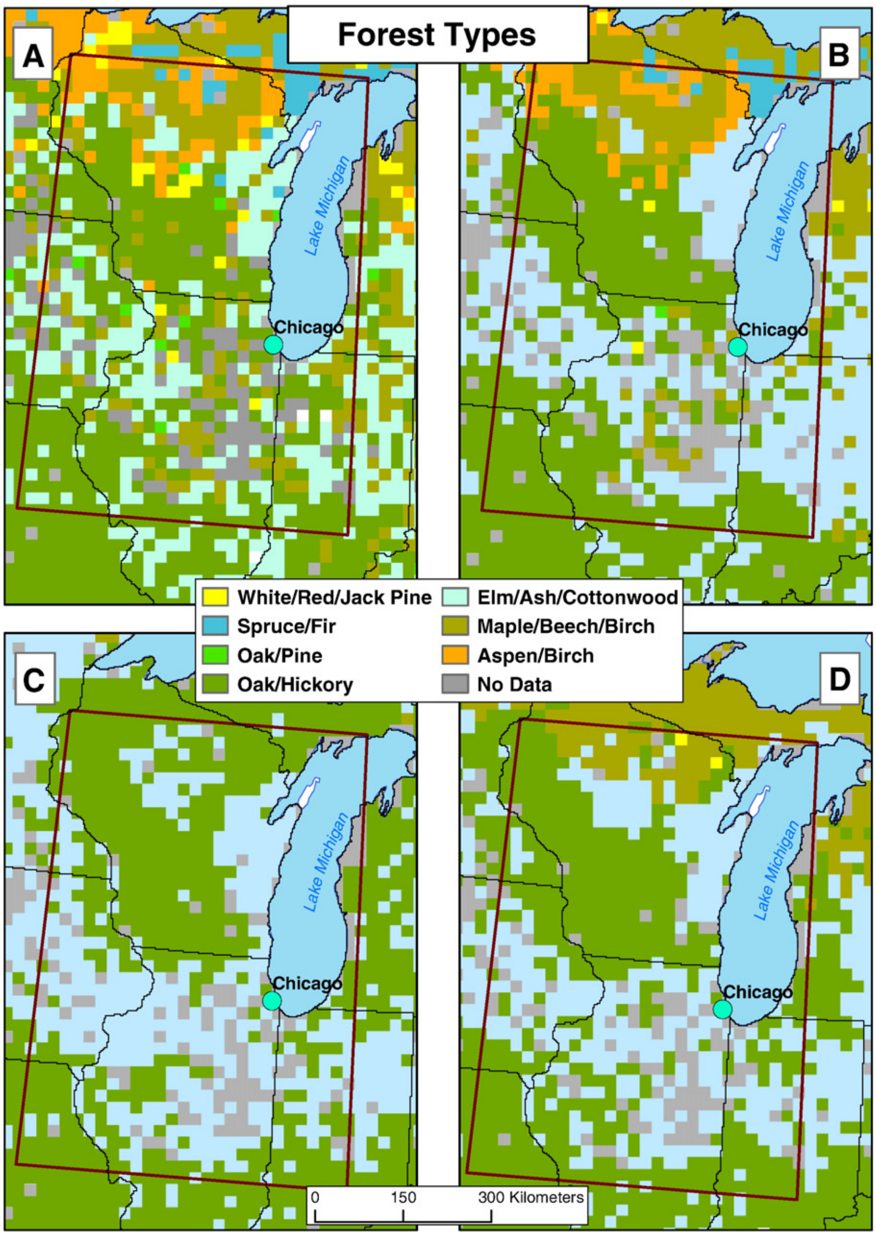

Fig. 3. Forest-type maps based on combining individual species maps of importance as measured (A), modeled under current conditions (B), and modeled under higher (C) and lower emission (D) scenarios for end-of-century. Redrawn from a larger geographic analysis in Iverson et al. (2008). Box indicates study area.

tree projections). With these climate data, we tabulated those species that may have a change in the distribution of their habitat and estimated the potential "winners" (i.e., those with gains in habitat) and "losers" (i.e., losing habitat) within the multi-state area around Chicago.

We project that habitats for 52 (low emissions) to 54 (high emissions) species would increase at least 10%, while 64 (low emissions) to 76 (high emissions) species would lose habitat within this area (Table 2; see brown box in Figs. 4 and 5 for boundaries of analysis). Of the losers, 37 to 42 species could lose more than half their total habitat, including: hermit thrush (*Catharus guttatus*), black-throated green warbler (*Dendroica virens*), winter wren (*Troglodytes troglodytes*), Canada warbler (*Wilsonia canadensis*), magnolia warbler (*Dendroica magnolia*), evening grosbeak (*Coccothraustes vespertinus*), dark-eyed junco (*Junco hyemalis*), Swainson's thrush (*Catharus ustulatus*), Lincoln's sparrow (*Melospiza lincolnii*), and common loon (*Gavia immer*) (Table 3). Also losing considerable suitable habitat could be American goldfinch (*Carduelis tristis*) (Fig. 4). Of the winners, 15 to 22 species could have increases in habitat by at least a factor of 5 within the Chicago region (Tables 2 and 3), including loggerhead shrike (*Lanius ludovicianus*), blue grosbeak (*Passerina caerulea*),

Table 2
Summary of potential changes in suitable habitat for 147 species of birds that live in the multi-state region surrounding Chicago (brown square in Figs. 4 and 5). Values shown are the ratios of future to current incidence scores, such that a ratio below one indicates a loss of suitable habitat, while a ratio above one indicates a gain. Total gainers (>1.1) were 52 species under lower emissions and 54 for higher, while total losers (<0.9) were 64 species under lower and 76 under higher emissions. Projections were based on average of simulations from three global climate models statistically downscaled to the U.S. Great Lakes region (see Hayhoe et al., 2010 for climate projections).

	<0.5	0.5–0.9	0.9–1.1	1.1–2.0	2.0–5.0	>5	NA in Chicago
Lower emissions	37	27	27	23	14	15	4
Higher emissions	42	34	16	14	18	22	1

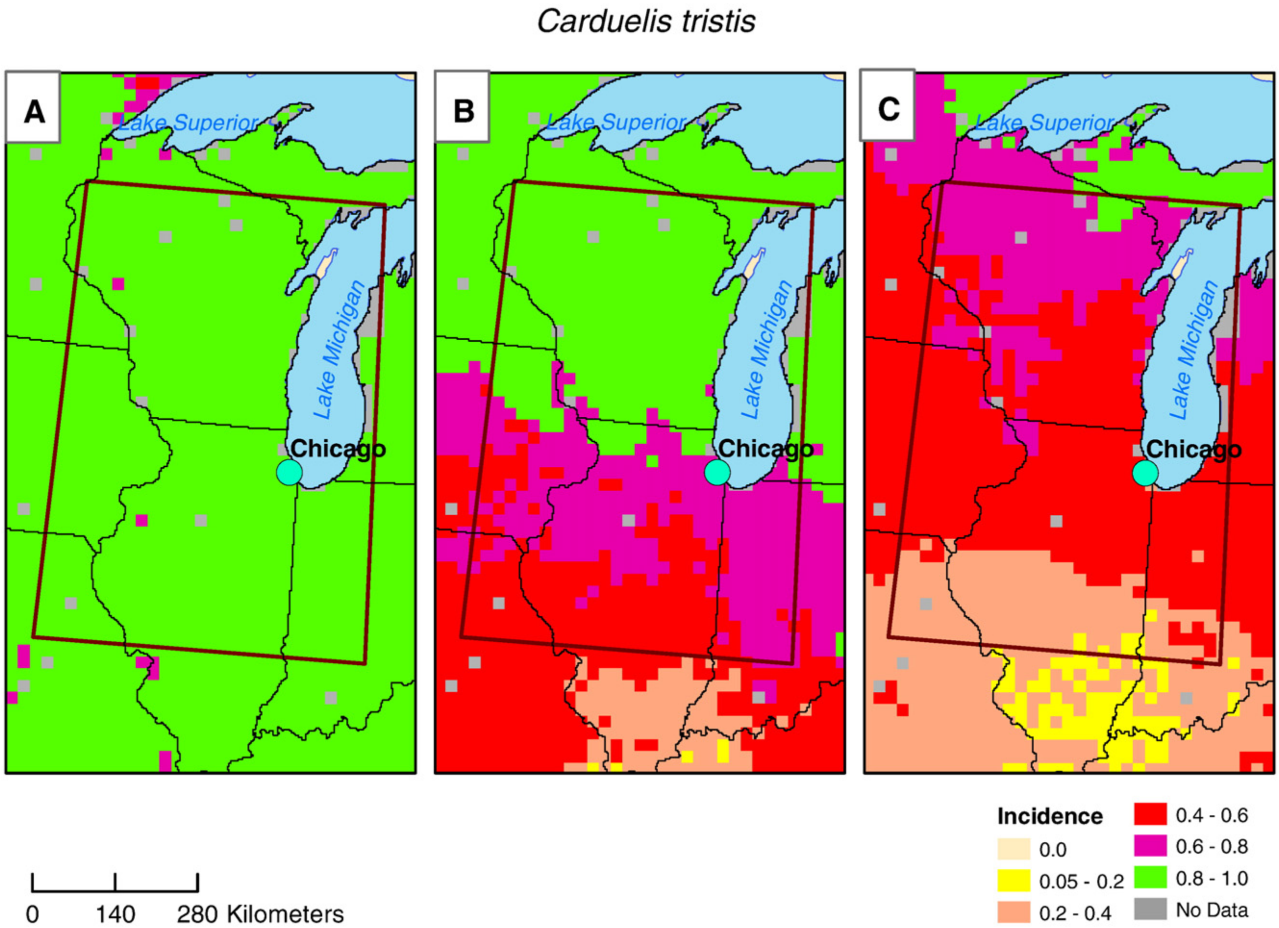

Fig. 4. Projected suitable habitat under climate change for one species that will likely undergo a regional decrease, the American goldfinch (*Carduelis tristis*). Panel A illustrates the historical distribution of the species based on data from the annual Breeding Bird Survey. Panel B is a projection based on the average of three climate simulations under a lower emissions scenario. Panel C is a projection based on a higher emissions. These models were based on climate, elevation, and potential future tree abundance. Redrawn from a larger geographic analysis in Matthews et al. (2007). Box indicates study area.

summer tanager (*Piranga rubra*) (Fig. 5), great egret (*Ardea alba*), chuck-will's widow (*Caprimulgus carolinensis*), red-shouldered hawk (*Buteo lineatus*), scissor-tailed flycatcher (*Tyrannus forficatus*), little blue heron (*Egretta caerulea*), and cattle egret (*Bubulcus ibis*).

These data suggest that, under the lower emissions scenario, there were 116 bird species projected to have habitat changes of at least 10% in the broad area near Chicago, with a net of 12 more species with projected losses than gains. Under the higher emissions scenario, habitats of 130 species could be altered, with 22 more species losing than gaining habitat, including many species of ecological, aesthetic, and economic importance (Tables 2 and 3).

Projected changes in the geographic ranges of butterflies also can be used to illustrate the potential impacts of climate change on animals in the Chicago region. Butterflies often depend on one or just a few specific plant taxa for food, and like most insects, they are sensitive to changes in temperature (Hellmann, 2002; White and Kerr, 2006). Because the geographic ranges of butterflies are better known than many other insect species, they lend insight into the general responses of insects. Using the online database of Butterflies of North America (Opler et al., 2006), we made simple projections about future changes in the butterfly community near Lake Michigan. A more sophisticated analysis of range changes, analogous to that discussed for birds above, has been performed for Canadian butterfly species (Peterson et al., 2004).

Based on the potential pattern of climate warming, we assumed that a species could go locally extinct if its historical, southern range boundary occurs in proximity to the southern Lake Michigan area and that it could appear in this area under climate change if it is currently occupying regions with a climate similar to future projections (e.g., southern Illinois, Tennessee, Kentucky, northern Alabama). This assumption is reasonable if the butterflies' resource base is widely available or responds to climate in a similar way to the animal itself (i.e., has similar climatic tolerances). The area around southern Lake Michigan currently contains 115 species of butterfly, of which we would expect 20 species to leave the region and 19 species could appear (Fig. 6). In addition, some species that currently reach their northern range boundary near southern Lake Michigan might become more abundant, including the hoary edge (*Achalarus lyciades*), southern cloudywing (*Thorybes bathyllus*), Horace's duskywing (*Erynnis horatius*), fiery skipper (*Hylephila phyleus*), Zabulon skipper (*Poanes zabulon*), pipevine swallowtail (*Battus philenor*), zebra swallowtail (*Eurytides marcellus*), spicebush swallowtail (*Papilio troilus*), cloudless sulphur (*Phoebis sennae*), sleepy orange (*Eurema nicippe*), juniper hairstreak (*Callophrys gryneus*), red-banded hairstreak (*Calycopis cecrops*), white M hairstreak (*Parrhasius m-album*), and goatweed leafwing (*Anaea andria*). The appearance of new species into any region is difficult to predict for butterflies because butterfly colonization is predicated on the existence of a suitable host plant. To encourage the establishment of southerly butterfly species, therefore, we also may need to assist in the migration and the establishment of appropriate host plants (McLachlan et al., 2007; Pelini et al., 2009).

For insects in general, warmer temperatures should accelerate development causing earlier emergence and a greater number of

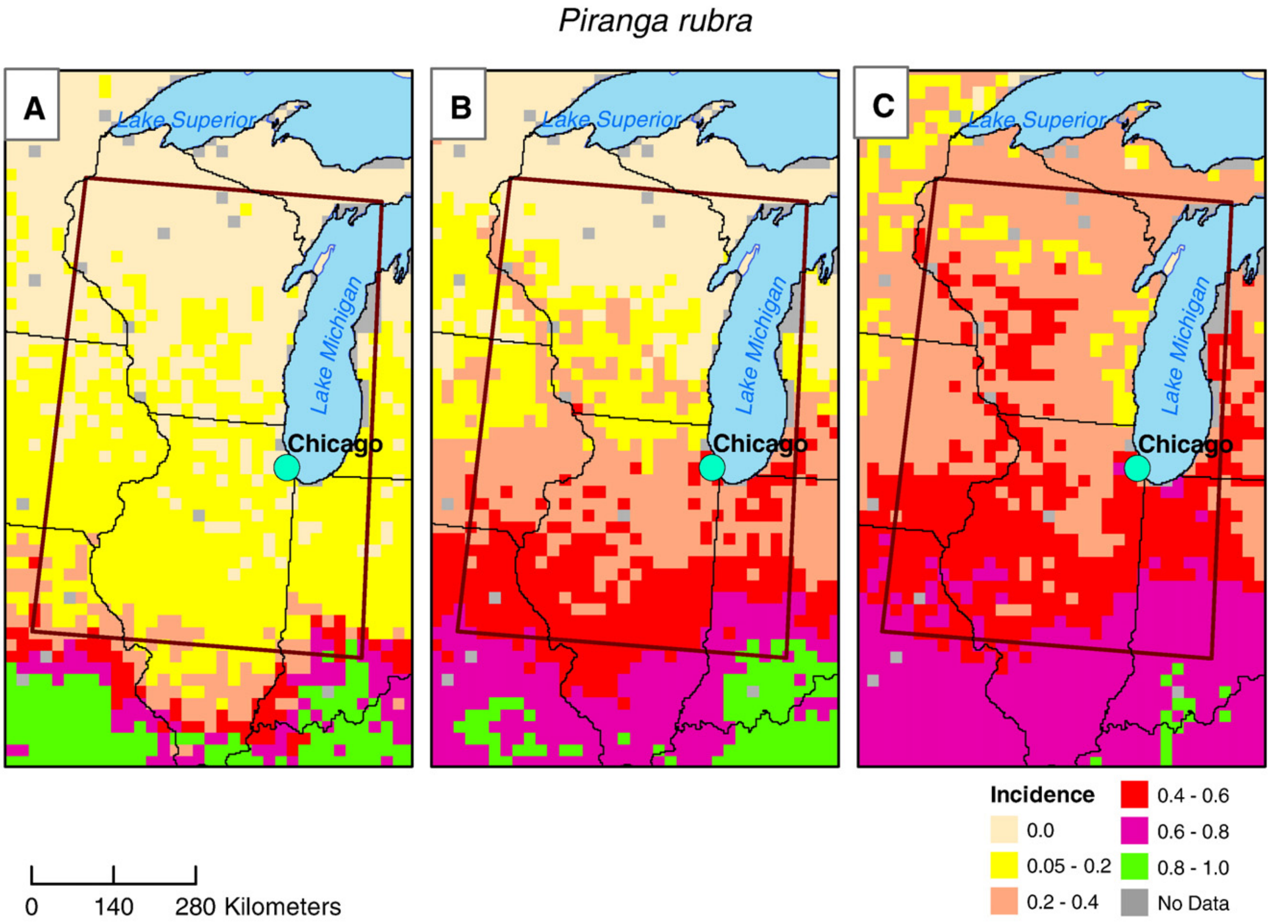

Fig. 5. Projected suitable habitat under climate change for one species that will likely undergo a regional increase, the summer tanager (*Piranga rubra*). As in Fig. 4, panel A illustrates the historic distribution; panel B is a projection under a lower emissions scenario; and panel C is a projection under a higher emissions scenario. Redrawn from a larger geographic analysis in Matthews et al. (2007). Box indicates study area.

generations per year, all other factors such as resource quality being equal. In the case of pest species, a greater number of generations per year can mean greater total damage (Logan et al., 2003). A number of more southerly pest species also may extend their ranges northward if climate change reduces overwintering mortality by raising minimum winter temperatures (Ayres and Lombardero, 2000). Projections for the southern pine beetle (*Dendroctonus frontalis*), for example, show the species reaching northern Indiana and occasionally even Minnesota if winter temperatures increase sufficiently (Ungerer et al., 1999; Ayres and Lombardero, 2000). Plants that are stressed by climatic factors (e.g., drought) or climate-related disturbance (e.g., fire) also may become more susceptible to insect pest or pathogen attack (Ayres and Lombardero, 2000; Dale et al., 2001).

The responses of mammals to climate change will vary strongly by species. Large species that move easily over considerable distances might be able to track climate change as long as habitats are available and if human residences and development do not block their way. Opossums (*Didelphimorphia*) and armadillos (*Dasypodidae*) provide good examples of this kind of response. Opossums barely extended to the southernmost Great Lakes region at the beginning of the 20th century. Over the past 110 years, however, they have extended their range northwards by at least 400 kilometers, encompassing most of Wisconsin and Michigan. Opossums do not fare well under cold conditions, and climatic warming has likely played an important role in their shift northwards in the Great Lakes region (Myers et al., 2009). Armadillos are following a similar trajectory but beginning much further south. Members of this species were reported in 1849 to be confined to the lower Rio Grande valley of Texas. They have gradually spread northwards since that time, with populations now established as far north as central Missouri, southern Kansas, and western Tennessee, and isolated reports of individuals in Nebraska and central Illinois (Van Deelen et al., 2002). The northern distribution of this species is thought to be limited by temperature and rainfall (Taulman and Robbins, 1996), and recent range expansion may have been aided by climatic change. Armadillos will likely become established through most of Illinois under either climate change scenario.

Armadillos and opossums are unusual, however, in that they are fairly large, mobile animals that do well around habitats modified by humans. Most large mammals known from the broad area around Chicago are either extinct or have been extirpated locally (bears, bobcats, wolves, elk, bison, etc.). A few others adapt well to habitats modified by humans and are very widespread in their distributions (e.g., raccoons, skunks, deer). They occur across wide areas of the United States and Canada and therefore are unlikely to be much affected by climate change near the southern Great Lakes. Small mammals (mice, shrews, bats), on the other hand, present a much more complicated picture with respect to their response to climate change. Illinois is a meeting ground for faunas from different regions of the country (Hoffmeister, 1989), and it is likely that climate change will result in a substantial modifications to the communities of small mammals in the state. Ranges will change through the direct physiological effects of temperature and precipitation on each species, or as change impacts individuals indirectly through modifications to plant communities. Some species now found only in the southernmost part of the state (e.g., golden mice (*Ochrotomys nuttalli*), cotton mice (*Peromyscus gossypinus*), southern short-tailed shrews (*Blarina*

Table 3
Cumulative incidence values (a metric of relative abundance) of selected bird species. Values are an indication of abundance and range for their current distribution, and for end-of-century under lower and higher emissions within the mapped area depicted in Figs. 4 and 5. "Current" indicates incidence according to modeled Breeding Bird Survey data, "Lower" indicates potential incidence in future under lower emissions (using average of three climate models), and "Higher" indicates potential future incidence under higher emissions. Bold letters indicate the species rank in the top 10 for all 147 species. Bold italic values indicate the species ranks in the bottom 10 among all species. The table thus shows the major current species, the major gainers, and the major losers under climate change.

Common name	Latin name	Current	Lower	Higher
American robin	*Turdus migratorius*	**957**	911.4	739.2
Common yellowthroat	*Geothlypis trichas*	**943.9**	812.6	554.8
Barn swallow	*Hirundo rustica*	**940.9**	952.3	928.8
Brown-headed cowbird	*Molothrus ater*	**939.8**	935.8	919.7
European starling	*Sturnus vulgaris*	**937.6**	909.4	793.3
Indigo bunting	*Passerina cyanea*	**936.5**	915.1	732.2
Mourning dove	*Zenaida macroura*	**930.6**	954.4	954.4
Song sparrow	*Melospiza melodia*	**929.5**	474.9	208.2
American goldfinch	*Carduelis tristis*	**928.5**	729.9	499.8
Killdeer	*Charadrius vociferous*	**912.8**	928.5	902.2
Hermit thrush	*Catharus guttatus*	99.2	***14.3***	***8.0***
Loggerhead shrike	*Lanius ludovicianus*	76.2	**470.4**	609.1
Black-throated green warbler	*Dendroica virens*	75.2	***11.7***	***7.1***
Winter wren	*Troglodytes troglodytes*	72.7	***7.6***	***3.9***
Common loon	*Gavia immer*	61.6	***10.8***	***5.7***
Blue grosbeak	*Passerina caerulea*	53.3	**396.4**	**524.1**
Canada warbler	*Wilsonia canadensis*	44.6	***7.1***	***4.3***
Summer tanager	*Piranga rubra*	39.5	**243.3**	**408.8**
Magnolia warbler	*Dendroica magnolia*	30.6	***4.5***	***3.0***
Evening grosbeak	*Coccothrustes vespertinus*	27	***2.6***	***1.0***
Great egret	*Casmerodius albus*	24.6	147.0	**279.4**
Dark-eyed junco	*Junco hyernalis*	16.3	***1.6***	***0.6***
Swainson's thrush	*Catharus ustulatus*	8.3	***0.0***	***0.0***
Lincoln's sparrow	*Melospiza lincolnii*	7.5	***0.3***	***0.0***
Chuck-will's widow	*Caprimulgus carolinensis*	3.1	**131.9**	**296.5**
Red-shouldered hawk	*Buteo lineatus*	2.8	**35.0**	**102.8**
Scissor-tailed flycatcher	*Muscivoria forficata*	1	**159.7**	**308.0**
Little blue heron	*Ardea herodias*	0.1	**204.4**	**438.4**
Cattle egret	*Bubulcus ibis*	0.1	**152.7**	**401.7**
Yellow-crowned night-heron	*Nyctanassa violacea*	0.1	**7.4**	**47.4**
Fish crow	*Corvus ossifragus*	0.1	**2.2**	**7.6**

carolinensis)) or in areas just outside the southern Illinois border (e.g., cotton rats (*Sigmodontinae*), eastern harvest mouse (*Reithrodontomys humulis*)) may increase in abundance and extend their distributions northwards. Illinois species at the southern edge of their distributions in the Midwest (e.g., masked shrews (*Sorex cinereus*), short-tailed shrews (*Blarina brevicauda*), southern bog lemmings (*Synaptomys cooperi*), meadow voles (*Microtus pennsylvanicus*)) may decline. Unfortunately, while we can say that change is very likely, our knowledge of the biology of the physiology or ecology of most of these species is not adequate to support strong predictions concerning their response to climate change scenarios.

Predicting responses of bats to climate change is an especially interesting problem. Illinois is home to approximately 13 species of bats. Several are found only in the southernmost part of the state (e.g., southeastern Myotis (*Myotis austroriparius*), gray bat (*Myotis grisescens*), Rafinesque's big-eared bat (*Plecotus rafinesquii*)), with some additional species found in bordering areas to the south (e.g., small-footed bat (*Myotis leibii*), Townsend's big-eared bat (*Plecotus townsendii*)). Bats are very sensitive to temperature because of their small size and large surface area. For example, they choose roosting and hibernating sites within very narrow ranges of temperature, wind speed, and humidity in order to spend essential calories efficiently (e.g., Humphries et al., 2002). In some species, the requirements of an individual, and therefore the roosting site it chooses, change over a season, apparently in response to modifications in the animal's reproductive condition or seasonal needs (Altringham, 1996). Populations of many bat species are believed to be limited by the availability of roosting and hibernating sites that meet these requirements, and so we can expect radical changes in the structure of the bat communities if climatic warming results in modifications in the thermal ecology of these sites. Accurately predicting how those changes will play out, and perhaps more important to farmers, what effect they will have on the populations of insects on which bats feed, is not possible given our current knowledge of these species and their habitats.

In northern Michigan, studies by Myers et al. (2005) indicate that deer mice, white-footed mice, southern flying squirrels and other small mammals have extended their ranges steadily northward, probably in response to climate change. There, large and uninterrupted tracts of forest provide a relatively easy route for movement. This is not the case near Chicago and southern Lake Michigan, an area heavily impacted by agriculture and human settlement. Further, the Great Lakes themselves are a barrier to movement. Analysis by Francl et al. (2010) of mammalian species trapped in northwest Indiana suggests that the Great Lakes and urban development in the metropolitan area could impede northward migration of some mammalian species. For example, in simulations of a higher emission scenario by Francl et al. (2010), some species "dead end" at the top of the lower peninsula of Michigan.

Finally, our consideration of animal impacts (above) does not explicitly consider changes in precipitation, or more precisely, the changes in seasonal water balances of ecosystems. Ecosystem water balances and water availability to animals could be reduced even under higher springtime or annual precipitation because of greater heat loads and more intense summer droughts. Changes in water balance could affect many animal species including flight activity and development time in insects and resource availability for birds and mammals. Species such as salamanders and frogs, which we have not

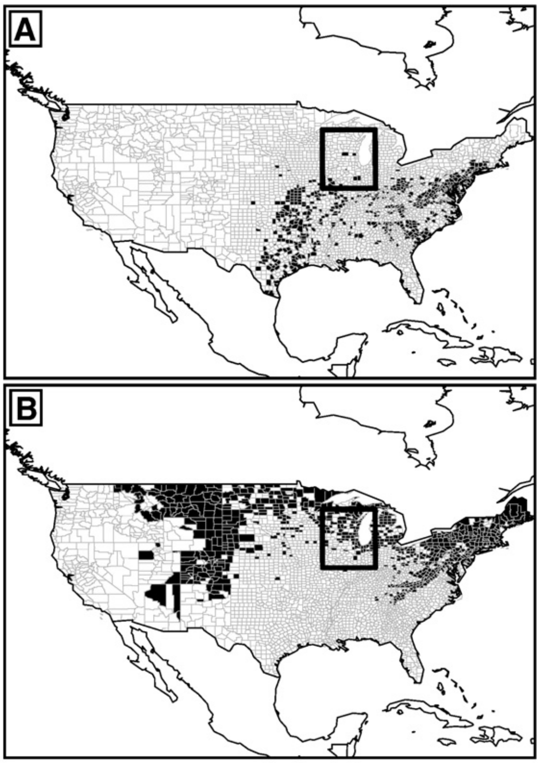

Fig. 6. Historical geographic distribution of two example butterfly species where symbols indicate counties where individuals have been observed. Species with a southerly distribution such as the falcate orangetip (*Anthocharis midea*) (A) may expand into the multi-state region surrounding Chicago. Northerly species such as the Aphrodite frittilary (*Speyeria aphrodite*) (B) may disappear from the region. Box near Lake Michigan is the same area as given in Figs. 1–5 above.

examined here, are likely to be particularly sensitive to changes in rainfall and water balance as this affects the duration of vernal pools and other ephemeral water resources (see Brooks, 2004; Rodenhouse et al., 2009). Unfortunately, ecological projections involving changes in precipitation require improved forecasting of both total precipitation and the periodicity and duration of precipitation events (Pyke, 2005); such projections also require a better understanding of the interaction of water balance with physiological limits of the organisms.

Invasive species, weeds, and climate change

Many invasive plants are known to respond to increased atmospheric concentrations of CO_2, suggesting that they will become more aggressive and more costly to control with increasing greenhouse gas emissions (Dukes and Mooney, 1999). These include species already occupying the broad area near Lake Michigan, such as spotted knapweed and Canada thistle (Ziska et al., 2004), and species that occur to the south that could spread into the region such as the aggressive non-native, kudzu (below). Changes in leaf defenses also can be associated with growth changes due to the fertilization effect of elevated CO_2. For example, elevated CO_2 could affect the attack rate of the invasive Japanese beetle on soybean, a key agricultural crop in the lower Great Lakes region (Casteel et al., 2007).

In addition to making some invasive species more aggressive, climatic change could influence the geographic spread of non-native species. By definition, invasive species are those that have expanded their ranges from areas of historical occupancy and that cause economic or ecologic damage in their new range. Some invasives are spreading under current climatic conditions due to human-mediated dispersal, and climate change could exacerbate invasives' rates of spread (Hellmann et al., 2008). Non-native species that we do not presently consider invasive also could become more harmful (Hellmann et al., 2008), and new invasive species could arrive if climate change brings new pathways of human movements that could carry non-native species. For example, new shipping channels associated with melting sea ice could link regions to Lake Michigan that have not been historic trading partners, and these could be sources of novel invasive species (Pyke et al., 2008).

A species for which there is great concern about range change is the gypsy moth (*Lymantria dispar*), a generalist defoliator that can cause tree death and increases the incidence of stress-related tree disease. Gypsy moth was introduced to Massachusetts in the mid-1800s, and the species has steadily spread westward, now covering Michigan, eastern Wisconsin, and northern Indiana. The Chicago region, on the current front of this spreading species' range, plays an important role in slowing the westward migration and damage of this species. Climate change could exacerbate the spread of this species and hinder efforts to keep the gypsy moth at bay, however. Like other overwintering insects, increases in winter temperature could accelerate the spread of gypsy moth by enabling larger population sizes to overwinter and allow an extended season of activity and breeding. Plants stressed directly by climate change or indirectly through some climate-mediated change in forest communities could face higher probabilities of attack by the gypsy moths attempting to colonize Chicago. Increasing CO_2 concentrations may also affect the likelihood of tree mortality when attacked by gypsy moth, but studies suggest that the direct effects of increased temperature on the development time of gypsy moth has a greater effect on moth dynamics than do indirect effects of CO_2 on leaf quality (Williams et al., 2003).

Another important invasive that could emerge near Chicago and the Lake Michigan area is kudzu (*Pueraria lobata*), an invasive species now causing extensive ecological and economic damage in the southeastern United States (Mitich 2000). Kudzu has spread from central Kentucky into southern Indiana and Illinois in the last 30 years. Recent studies suggest that this spread is due to rising minimum winter temperatures that no longer dip below the plant's lethal temperature (Ziska and George, 2004). If this rate of winter warming were to continue, kudzu could reach the Chicago region and central Wisconsin and Michigan (45° north latitude) by 2020 (Ziska et al., 2008; Fig. 7). Unlike many native species with range shifts that may be impeded by urban and suburban development, kudzu thrives in urban landscapes.

Climate change and agriculture

Because agriculture is so widespread in the multi-state region around Chicago and is used as habitat by many species, it constitutes a “terrestrial ecosystem.” Agriculture in this region, as in much of the Great Plains, is dominated by a soybean/corn rotation. At the state level in Illinois, for example, soybean and corn together contribute approximately 5 billion dollars, respectively, to the 8 billion dollar agricultural economy of the state (NASS, 2002). Illinois ranks third nationally in total prime farmland acreage, which covers nearly 80% of the state's land area. Additional economic inputs from agricultural machinery, manufacturing, and value-added food products also provide additional billions of dollars to the greater Chicago region economy.

Soybean production is sensitive to temperatures greater than 35 °C during flowering (Salem et al., 2007). Specifically, an estimated average 17% decline in soybean yield occurs for every 1 °C rise in temperature (Lobell and Asner, 2003). For soybean grown in northern Illinois, for example, this would suggest declines of 30% and 55% under the lower and higher emission projections, respectively, by the end of the century (Hatfield et al., 2008). Corn, in contrast, is thought to be less susceptible to increased temperatures because it is a tropical grass (Hatfield et al., 2008).

Temperature and precipitation are physiologically highly interrelated with regard to regulating plant productivity. While all future climate scenarios project increasing temperatures with a high degree of certainty, uncertainties in the magnitude and sign of precipitation change are high among models and scenarios. For the Midwest, models are consistent in projecting increases in winter and spring precipitation, with projections of little change to decreases in summer and fall (Hayhoe et al., 2010). Increasing summer temperatures would increase water demand and even if precipitation were to increase, could cause reduced production. Increasing spring precipitation also could delay planting and could impose damage on early germination and emergence of corn and soybeans. Under the higher emissions scenario in particular, decreases in summer precipitation are possible, with subsequent substantial declines in crop production. Even if seasonal average precipitation remains constant, the projected shift in the distribution towards more intense precipitation events (punctuated by longer dry spells) could increase the risk of flooding and storm damage with detrimental effects on field activities, most notably harvesting with subsequent loss of revenue.

Crop plants are likely to respond to increases in atmospheric CO_2 concentration because their growth is less dependent on nutrient limitation than is growth in more natural, non-fertilized ecosystems. Recent and projected increases in atmospheric CO_2 levels could therefore benefit agriculture because rising CO_2 could either directly stimulate photosynthesis or allow greater water conservation through increases in water use efficiency because of less stomatal opening. However, initial research suggests that any positive effect of increased CO_2 on plant yields may not always compensate for the negative effects of increased heat stress (Jifon and Wolfe, 2005; Matsui et al., 1997). In addition, there are a number of reports indicating differential stimulation of weeds relative to crops in response to rising carbon dioxide, with subsequent reductions in crop yields (e.g., Ziska and Goins, 2006).

If yields are compared in a north-south line from the Great Lakes States to the Gulf States, losses due to weeds increase from 22% in the

Fig. 7. Change in county-level distribution of kudzu (*Pueraria lobata*) populations for Illinois, USA, from (A) 1971 and (B) 2006. Data are given for Illinois because it represents the current range front. Estimates in panel A are taken from maps drawn by Clyde Reed, a USDA researcher, from 1970. Estimates in panel B were created using: National Resource Conservation Service (NRCS), database of invasive U.S. Species (plants.usda.gov/java/profile?symbol = PUMO); the National Agricultural Pest Information Service (NAPIS) in cooperative agreement between the Animal Plant Health Information Service (APHIS) and Purdue University as part of their Cooperative Agricultural Pest Survey (CAPS) program (ceris.purdue.edu/napis/pests/weeds/imap/kudzu.html); and the Department of Natural Resources (DNR) for Illinois, including the publication of "The Green Plague Moves North" by the Illinois DNR. Panel C indicates the location of Illinois within the Great Lakes region indicating the same area boxed in Figs. 1–6.

north to 35% in the south for corn, and 22% in the north to 64% in the south for soybean (Bunce and Ziska, 2000). Under future climate change, it cannot be assumed that greater weed-induced crop losses could be compensated for by increased chemical control (Archambault, 2007). In addition, warmer temperatures may allow the spread of highly aggressive weeds such as kudzu (e.g., Fig. 7), which is not only disruptive to agriculture, but which also acts as a host to soybean rust.

As Chicago and other neighboring metropolitan areas expand, greater pressure will be brought to bear on agricultural land and competition between urban and rural needs is likely to intensify. It is unclear at present how additional economic demand for corn-based ethanol, biomass, or food products in general will affect land use changes in this region. These indirect effects of climate change, changes motivated by a desire to reduce greenhouse gas emissions, could have significant consequences for land conservation, just as the effects of climate change will have conservation consequences (Pyke et al., 2008).

Recommendations

The multi-state region around Chicago will experience profound ecological changes due to climate change. We make this statement because this region is composed of a complex landscape mosaic of urban, suburban, and agricultural development that already poses limitations for native, terrestrial ecosystems. The region also is unique because of a major dispersal barrier (Lake Michigan) and its location in the midst of an ecotonal transition between prairie and eastern woodland and between the central and northern hardwood forests. These features imply the need and opportunity for creative, adaptive solutions that promote healthy natural systems undergoing the impacts of climate change. They also reinforce the need for greenhouse gas mitigation so that the negative consequences for native biota, ecosystem services, and agricultural production can be minimized in the region. As a major metropolitan area with aspirations for national policy leadership, Chicago and other neighboring cities and communities could develop new biodiversity management techniques while also pursuing aggressive mitigation.

A suite of management strategies are needed to build resilience (or so-called adaptation) into the natural landscape (CCSP, 2008). First, a high priority should be placed on maintaining and restoring native ecosystems, particularly wetland ecosystems, because these systems can partially buffer the effects of increased storm intensities and provide natural cooling from extreme heat events (Foley et al., 2005). In addition, riparian and other preserves serve as biodiversity "hot spots" and corridors in the region, providing habitat for various fishes, amphibians, reptiles, birds, and mammals. Several key riverine systems in the region, such as the Des Plaines, Fox, Rock, and Chicago River, trend in a north-south direction, and these systems can serve as migration corridors for various plant and animal species that may need to shift their geographic distributions northward under regional warming. For such corridors to function, however, they will need to capture the full complement of ecosystem types, including some upland habitats. Where these habitats are missing across the region, restoration in strategic locations will be necessary. Such restoration should also consider climate change. For example, historical dominants may no longer be the best species for use in restoration (see assisted migration below). The removal of other anthropogenic stressors also should enhance the resilience of existing, natural systems to climate change (CCSP, 2008), though such action will not likely overcome dispersal barriers that species encounter when migrating in response to climate change.

Second, strategies for helping species move through the urban and suburban landscape need to be researched and developed for the region. Migration routes through Chicago, up the west side of Lake Michigan, may be important for species to keep pace with changing climatic conditions. Such “assisted migration” could take the form of encouraging populations of species with northern boundaries in the region or active introduction of more southerly species into locations within or north of urbanized areas. The latter is a more aggressive and controversial technique, but it might be warranted in some cases, particularly under high emission scenarios and for species with small, isolated distributions. Alternatively, areas in the landscape that are buffered from climate change by geographic features or unique climatic phenomena could serve as refugia, places where traditional conservation could be concentrated because the threats from climate change are minimized (CCSP, 2008). Refugia may be a particularly good option, or one prong in a diverse strategy, for habitats near Lake Michigan. The Lake has a significant effect on local climate, particularly in close proximity to the Lake or east of the Lake in Michigan and Indiana (Denton and Barnes, 1987). If refugia are not sufficiently numerous or not effective for particular taxa, additional strategies will be needed. More research is needed to determine the relative effectiveness of conservation strategies (Hellmann et al., in press).

Third, where ecosystem preservation or restoration is not possible, other forms of green space should be encouraged such as cluster housing with interspersed undeveloped land, or generous parks with area left in natural states (Forman, 1995; Farr, 2007). A large number of native species in the broader area around Chicago can persist in human-dominated landscapes; hence, residential green space can be used to augment natural preserves, increasing the population of some species and providing habitat for species that might migrate through the region as they track changing climatic conditions. Importantly, a progressive attempt at managing the entire mosaic, including the “matrix” of built-up lands, is clearly needed.

Complementary to strategies that encourage resilience of native ecosystems, strategies must be developed to prevent, or at least greatly slow, the spread of harmful species that might benefit from climate warming. Monitoring will need to be a major component of such strategies. Invasive pests like the gypsy moth already demand management attention, and managers should intensify those efforts in anticipation of increased threats due to direct or indirect effects of climate change. In many cases, invasive species have broader tolerances than native species and thus some pest problems might grow under regional climate change (Hellmann et al., 2008). Some recent data suggest that cities may protect themselves against such invasion from kudzu, for example, by promoting native green space and minimizing disturbance of intact ecosystems (Mandryk and Wein, 2006). Many of these efforts to control the spread of invasive species will need to take place in the “matrix” of developed land as well (Epanchin-Niell et al., 2009).

The multi-state region including Chicago needs to pursue cutting-edge strategies for the adaptation of agriculture and agricultural landscapes that provide sustainable agricultural yields but also sustenance for native wildlife. Although the challenges posed by climate change for farming are substantial, there are a number of potential adaptation strategies available for farmers. For example, adjusting planting and harvesting dates, planting more heat-tolerant varieties or switching to warmer season crops (e.g., melons) are among the first-line options. However, long-term adaptation may also involve larger capital investment in irrigation, crop storage or livestock facilities, and information-intensive decision-making which may impose a greater financial burden on smaller family farms.

Climate change could also provide opportunities for farmers to develop win–win strategies, such as sustainable farming practices that also increase carbon sequestration, or use of marginal land currently under cultivation for permanent-cover bio-fuels as a means to increase income (Tilman et al., 2006). Overall, an increased focus on agricultural research is justified as a means to identify management strategies and mitigation options for farmers. Such research could be used to screen heat-tolerant or CO_2-sensitive lines of soybean (i.e., lines that could more effectively convert CO_2 increases into seed yield), identify ongoing and future pest problems, and determine potential economic opportunities that could simultaneously benefit farmers and the environment. Urban agriculture and reliance of consumers on regionally produced agriculture also can be an important part of greenhouse gas mitigation (McGranahan and Satterthwait, 2003).

Climate change biology and adaptation science are relatively young fields. There are few generalities that characterize species' responses to climate change, and the region that we have considered here has relatively few case studies to inform terrestrial ecosystem management. This should not stop managers from adopting creative and proactive management practices, however; as well, approaches can be adapted as more information is gained.

Finally, though we can learn much from current modeling techniques, such as shown here for potential species' habitat changes, a great deal of uncertainty remains regarding the interacting factors that influence potential species' response to climate change (Pearson and Dawson, 2003; Ibáñez et al., 2006). These models provide a broad perspective of distributional patterns to shed light on potential regional changes, but they cannot account for fine-scale variability and biotic and abiotic interactions. Therefore, models that incorporate dispersal, particularly through urban and developed areas, and which include interactions among species, are critical and are needed to refine projected responses of species to climate change. The climate crisis is upon us, and leadership among scientists, land managers, and policy makers is required to minimize the impacts on local residents, and indeed, on all the ecosystems around the globe.

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