Land Use, Climate Change and Ecosystem Services

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1 Introduction

Recent studies, including those by the Intergovernmental Panel on Climate Change (IPCC 2001a; 2001b; 2007a; 2007b), indicate that greenhouse gas (GHG) emissions and resultant atmospheric concentrations have led to changes in the world's climate, including increases in temperatures, extreme temperatures, heat waves, droughts, and rainfall intensity. Such changes are expected to continue, with substantial impacts on a range of land uses. Agriculture is potentially the most sensitive economic sector to climate change, given that agricultural production is highly influenced by climatic conditions. Changes in climate can have direct effects on crop yields and production costs, as well as indirect effects on relative crop prices. Each effect can drive changes in cropping patterns.

In view of its importance to economic well-being, effects of climate change on agriculture have been well researched and documented, dating back at least 25 years (see Adams et al. 1990; Zilberman et al. 1994; and various IPPC reports). A recent review of climate change and agricultural effects and adaptations, including land use, is found in Aisabokhae et al. (this volume).

Adaptation, in the form of changes in crops and their locations, is the most likely immediate reaction of agricultural producers to climate changes. Crop production, for example, is expected to increase in high latitudes and decline in low latitudes (see Adams et al. 1990; Zilberman et al. 2004; Aisabokhae et al. 2012, this volume; or IPCC 2007b; 2007c). Research generally suggests that current zones where crops are suitable may shift more than 100 miles northward In the US, northward shifts in the crop production mix have already been observed. Southern sections of traditional wheat-producing regions are now northern sections of corn-producing regions, as is already being observed in North Dakota (Upper Great Plains Transportation Institute 2011).

The combination of changes in rainfall, temperature, and increase in CO_2 concentration can also affect the productivity of pasture and rangelands, which are an important input for livestock production, and are an important source of wildlife habitat. Pasture production tends to increase in humid temperate grasslands, but is likely to decrease in arid and semiarid regions (IPCC 2007b), although climate change may decreases stocking rates (Mu and McCarl 2011). The combination of a northward shift in crop production and decreasing productivity of pasture and rangeland could lead to substantial conversion of land from low-intensity agricultural uses to intensive crop production. Conversion of grassland systems (i.e., pasture and rangeland) to crop production is associated with losses of grassland dependent species (Green et al. 2005), releases of sequestered carbon (Foley et al. 2005), decreases in water quality (Moss 2008), and increases in soil erosion (Montgomery 2007). Shifts in crop production have been hypothesized to have important environmental and ecological consequences. These include increases in air and water pollution as land is converted to more intensive cropping systems, and the reduction of ecological diversity provided by these altered landscapes. These various environmental and ecological effects are discussed in IPPC (2007b).

The purpose of this chapter is to discuss the linkages between climate change, changes in agricultural land use patterns and the ecological performance of these altered landscapes. The chapter first reviews the literature on the relationship between these topics, including studies assessing farmers' adaptations to a changing climate, and possible changes in flora and fauna triggered by land use changes. This is followed by an empirical study directed at one important consequence of such behavior – the effects of changes in agriculture land use on the ecological performance of wetlands in the Prairie Pothole Region of North America (PPR), as measured by wetlands and waterfowl abundance.

The PPR is a useful case study area because it is experiencing the effects of climate change and rapid changes in cropping patterns. The PPR is characterized by highly productive agricultural land, producing coarse and small grains, legumes and livestock, interspersed with millions of prairie pothole wetlands. Though many of the historical wetland-grassland complexes in the PPR have been previously altered by agriculture (Tiner 1984; Kantrud et al. 1989), the region remains the most productive waterfowl breeding area in North America (Batt et al. 1989). Climate change has the potential to significantly alter the productivity of the PPR for waterfowl; both through direct effects on wetlands (e.g., fewer wetland due to increased drought frequency) and through the indirect effects of human response (i.e., land use change). Thus this region offers an excellent case study for understanding the interplay between climate change, human response and ecological outcomes.

2 Literature Review

This section first reviews the existing literature on potential climate change impacts on land use in US agriculture and associated adaptive response with specific focus on changes in crop production patterns. This is followed by a review of ecological effects which may arise from the interplay of climate change and agricultural land use changes. Finally, we review previous studies related to the response of waterfowl to climate change and land use.

2.1 Change in US crop production pattern as an adaptive response to climate change

There are a number of ways that land use can be affected by climate change. For example, climate change, through changes in temperature, precipitation, extreme events, and snow cover, can induce changes in land values and land productivity through changes in water supply, increased fire risks, productivity of crops, forests, pastures, and livestock, and spatial and temporal distribution/proliferation of pests and diseases (see Aisabokhae et al., this volume)

Change in crop production patterns is one immediate adaptive response of agricultural producers to changes in land value and land productivity. Crop production is expected to increase in high latitudes and decline in low latitudes since increases in precipitation are likely in the high latitudes, while decreases in rainfall and increased risk of drought are likely in most subtropical land regions. Reilly et al. (2003) construct the geographic centroid of production for maize and soybeans and plotted its movement from 1870 (1930 for soybeans) to 1990. They find that both US maize and soybean production shift northward by about 120 miles. Similar result for corn and soybeans is shown in Beach et al. (2009) and Attavanich et al. (2011). For example, Attavanich et al. (2011) find that the production-weighted latitude and longitude of national production trended northwest from 1950-2010by approximately 100 and 138 miles for corn and soybeans, respectively.

Most studies conclude that changes in crop yields and relative crop prices induced by climate change will result in northward shifts in cultivated land (see e.g., Adams et al. 1990; Attavanich et al. 2011). The Lake states, Mountain states, and Pacific region show gains in production; the Southeast, the Delta, the Southern Plains, and Appalachia generally lose. Results in the Corn Belt are generally positive. Results in other regions are mixed, depending on the climate scenario and time period.

Attavanich and McCarl (2011) find that percentage of planted acreage of corn, sorghum, soybeans, cotton, and winter wheat increases the most in Appalachia, Corn Belt, Mountains, and

Pacific regions, respectively. Their results indicate that more cropland would shift to pasture/grazing land under climate change.

2.2 Effects of land use changes on ecological performance

The extant literature on agricultural effects and adaptations demonstrates clearly that changes in the agricultural landscape are likely to occur as a result of climate change. How these changes translate into changes in ecological performance require information from the natural sciences.

A substantial literature exists on potential effects of climate change on the environment (i.e. air and water) as well as ecological effects on flora and fauna. Some of this literature deals only with the physical and biological basis of such effects. Other studies tie these effects to economic outcomes, such as the costs of mitigating climate effects on environmental quality or ecological services. Still another set of studies include the relationship between climate and economic drivers of landscape (e.g., changes in forest or agricultural landscapes arising from changes in temperature or precipitation or changes in crop prices) on these environmental and ecological outcomes.

A comprehensive summary of these effects is beyond the scope of this chapter. Various IPCC reports summarize possible environmental and ecological effects (IPCC 2007b). What is clear is that climate change is expected to adversely affect a range of plant and animal species. For example, Hoegh-Guldberg et al. (2007) review previous studies and conclude that if atmospheric CO_2 is stabilized at 380 part per million (ppm), coral reefs will continue to change but will remain coral dominated and carbonate accreting in most areas of their current distribution. However, if atmospheric CO_2 is between 450 – 500 ppm, the density and diversity of corals on reefs are likely to decline, which could lead to largely reduced habitat complexity and loss of biodiversity, including losses of coral-associated fish and invertebrates.

Sekercioglu et al. (2008) assess risks of bird extinctions caused by climate change. They reveal that for land birds, approximately 400-500 bird extinctions by 2100 are projected under intermediate scenarios (surface warming 2.8° C by 2100 with 50 percent of lowland bird species assumed to adjust their geographical and topographic distributions in response to warming), while up to 2,498 extinctions (30% of all land birds) are forecasted under extreme scenarios (surface warming 6.4° C by 2100 with all species assumed to adjust their distributions). In another study addressing avian species, Jetz et al. (2007) estimate projected impacts of climate change and land-use change on the global diversity of birds. They predict that 11-21 percent of land bird species in the world could be endangered by climate change and land conversion by 2100 under the four Millennium Ecosystem Assessment (MA) global scenarios. They also suggest that land conversion (e.g., deforestation and conversion of grasslands to croplands) could have a much larger effect on species that inhabit the tropics.

Effects on mammalian species are also noted. For example, Welbergen et al. (2008) study the effects of temperature extremes on behavior and demography of Australian flying-foxes. They find that on 12 January 2002 in New South Wales, Australia temperatures exceeding 42.8°C killed at least 3,679 individuals in nine mixed-species colonies. The impacts of these temperatures had differential effects across sub-species, with the tropical black flying-fox experiencing a greater mortality rate than the temperate grey-headed flying-fox.

Reptiles and amphibians are also likely to be effected by climate change. During field-level monitoring of nests at an alpine site in southern Australia for the period 1997-2006, Telemeco et al. (2009) found that lizards (Bassiana duperreyi, Scincidae) responded to rising ambient temperatures by increasing their nest depth and increasingly early oviposition; however, they were unable to adjust themselves entirely to climate change. They reveal that rising ambient temperatures is likely to affect their hatchling sex ratio.

Finally, numerous studies had documented a wide range of effects of climate change on plants, both naturally occurring and managed, such as forest and agriculture. For example, Feeley and Silman (2010) report the effects of land-use and climate change on population size and extinction risk of Andean plants. They find that plant species from high Andean forests may benefit from climate change and expand their population under a scenario that beneficial land-use change practices are adapted and deforestation is halted (best- case scenario). On the other hand, if the pace of future climate change exceeds their abilities to migrate (worst-case scenario), all of these Andean species are projected to experience large population losses and consequently face risk of extinction. Moreover, all species are projected to experience large population losses regardless of potential migration rates under a business-as-usual land-use scenario.

An example of a study explicitly linking landscapes to climate change and plant species is by Lawson et al. (2010). This study links a spatially explicit stochastic population model to dynamic bioclimate envelopes to investigate cumulative effects of land use, changed fire regime, and climate change on persistence of a rare, fire-dependent plant species (Ceanothus verrucosus) of southern California. They reveal that climate change is the most serious factor determining the reduction of this plant species' population. Interactions of climate change with changes in fire regime and land use change could increase risk to these species.

2.3 Integrated assessments of climate change, land use and ecological performance

As noted above, numerous studies over the past two decades have linked economic behavior, changes in land use patterns and climate change. Most of these relate to agricultural and forest landscapes. A subset of this literature has looked at the coeffects of land use changes on ecological services and environmental quality, with climate change either directly or implicitly assumed. These studies have examined the economic impacts of such land use changes or the cost of mitigating for these changes on the ecological or environmental metrics of interest. Some representative studies are discussed below.

Wu et al. (2004) explored the influence of cropping pattern changes in the mid-west U.S. on regional water quality and ultimately on hypoxia potential in the Gulf of Mexico. They found that changes in cropping patterns (e.g. more corn-less pasture) and practices (e.g. minimum tillage) affected the run-off and erosion levels within the region. Although climate change was not explicitly examined, the underlying modeling included the influence of differences in weather variables across the region. A number of studies have addressed the relationship between forest cover, riparian zone health and water quality. For example, Watanabe et al. (2006) examined such relationships in the Pacific Northwest. The water quality parameters of interests were stream temperatures, which if elevated can adversely affect cold water species such as salmonids. The study noted that even active management of such landscapes, such as tree planting or riparian zone protection, have limited potential to reduce water temperatures to desired levels. Other studies, such as Langpap et al. (2011) or Seedang et al. (2008) also noted the difficulty (high costs) of obtaining reductions in water temperature through forest and riparian mitigation activities when landscapes have been extensively altered by human activities.

Pattanayak et al. (2005) performed an analysis of water quality co-effects associated with greenhouse gas mitigation activities on agricultural lands in the U.S. As with other studies examining carbon sequestration on agricultural lands, the study found substantial carbon sequestration potential from use of alternative cropping practices on agricultural lands. However, the study also found that such sequestration had an ancillary effect on national water quality. Specifically, the authors noted that overall water quality increased by 2 percent as a result of the sequestration practices. In another study of co-effects (co-benefits) of climate change mitigation policies, Plantinga and Wu assess the potential positive externalities of afforestation to sequester carbon. The authors find substantial benefits in terms of improved water quality (reduced soil erosion) and increased wildlife habitat from an afforestation policy.

In discussing effects of land use changes on ecological or environmental services, it is important to note that climate change is expected to have impacts on both the participation patterns of recreationists as well as their willingness to pay to experience recreation activities, In addition, it is expected that their willingness to pay for preservation of environmental services (non-use values) will be affected. Loomis and Crespi (1999) review the recreation literature regarding climate change and conclude that climate change will increase both participation rates and willingness to pay. Loomis and Richardson also confirm the effects of climate change on willingness to pay for ecological services. These findings suggests that any changes in ecological and environmental services arising from climate change-induced land use changes will have a greater economic impact in the future.

2.4 Response of waterfowl to climate change and land use

Waterfowl production in the PPR is highly dependent on the quantity and quality of wetlands, and on the suitability of upland land cover for nesting. Thus, a robust body of research has examined the relationship between wetland and grassland habitats, and waterfowl production (see e.g., Batt et al. 1989). In general, waterfowl populations are highly correlated with the number of wet basins, which generates the historic boom-and-bust cycle in waterfowl populations (Baldassare and Bolen 1994)). Additionally, upland land cover, which provides critical waterfowl nesting habitat, can mitigate or exacerbate the effects of pond numbers. Waterfowl nest success is generally higher in large blocks of native grassland (see e.g., Stephens et al. 2008), and lowest when wetland complexes are surrounded by intensive crops (Cowardin et al. 1983). While waterfowl can adapt and persist in the margins of cropland (given sufficient wetlands), population growth rates tend to decrease significantly in highly fragmented landscapes (Klett et al. 1988).

Given the importance of both wetlands and upland land use, climate change has the potential to substantially affect waterfowl productivity in the PPR. Some research has explicitly considered the effect of climate change on wetland functions in the PPR (Poiani et al. 1996; Johnson et al. 2004; Johnson et al. 2005; Johnson et al. 2010). In general, this research concludes that the increases in temperature predicted for the PPR will result in shorter hydro periods and less dynamic wetlands. With sufficient warming (e.g., + 4°C) much of the PPR will lack wetland conditions necessary to support waterfowl nesting. The effects of climate change on wetland productivity, however, are heterogeneously distributed across space, with optimal conditions shifting east as climate warms (Johnson et al. 2010).

Other research has demonstrated that the effects of climate change on wetland productivity depend on upland land-use (Voldseth et al. 2007). Upland land uses effects hydrological processes and vegetation dynamics, and therefore influences downstream prairie wetlands. Some wetland characteristics improve when uplands are in managed cover (e.g., managed grassland or crops) because these covers increase water delivery to wetlands. Voldseth et al. (2009) explicitly found that managed covers could partially mitigate climate effects on wetland function; however, the authors note that while the wetland may appear more dynamic when surrounded by managed covers, waterfowl production would be limited due to a lack of adequate nesting habitat.

The research on climate impacts on wetlands and land use impacts on waterfowl suggests that climate change could dramatically reduce waterfowl production in the PPR. Research using historical climate and land use patterns indicates that conversion of grassland to crops in the Canadian prairies exacerbated the effects of low water years (Bethke and Nudds 1995). Additionally, Sorenson et al. (1998) found a strong correlation between drought indices and waterfowl populations in the US PPR, and predicts that climate change could reduce waterfowl population by as much as 70% compared to historical levels. Their analysis, however, did not include the possible effects of change in upland land use. Although the past literature establishes the importance of both climate and land use, none of the previously developed models are capable of predicting the joint effect of climate change and the resulting land use response on waterfowl production in the PPR.

3 Model Components, Data, and Process Overview

To examine the response of waterfowl due to direct effect of climate change through changes in temperature and precipitation; and indirect effect through shifts in crop production patterns under alternative climate scenarios, this study employs three models. In this section, we provide a detailed description of the two component modeling systems, data used, and then discuss the model that links the two.

3.1 Model Components and Data

3.1.1 Agriculture Sector Model

We use an Agriculture Sector Model (ASM) to analyze the complex market mechanism that would occur in the agricultural sector as a result of climate change. The ASM has been developed on the basis of past work by McCarl and colleagues (McCarl and Spreen 1980; McCarl 1982; Chang 1992; Schneider et al. 2007). It has been used in climate change related studies for the IPCC, Environmental Protection Agency (EPA), and United States Department of Agriculture (USDA).

In brief, the ASM model is a price endogenous, spatial equilibrium mathematical programming model of the agricultural sector in the US. It includes all states in the conterminous US, broken into 63 agricultural production subregions and 10 market regions (See Appendix Table A1). It also captures land transfers and other resource allocations within the US agricultural sectors.

Simulated changes of crop yields under climate change scenarios are vital for this study since climate change affects crop yields, which influences the relative profitability of alternative land uses. We obtain simulated changes of crop yields from Beach et al. (2009). They use a modified version of the Environmental Policy Integrated Climate (EPIC) model, which was first developed by Williams et al. (1984), to simulate yield changes of 14 crops[1]. The authors use projected climate scenarios from four global circulation models (GCMs)[2] used in the 2007 IPCC assessment report with the IPCC SRES scenario A1B, which is characterized by a high rate of growth in CO_2 emissions. The scenarios are derived from:

- GFDL-CM 2.0, GFDL-CM 2.1 models developed by the Geophysical Fluid Dynamics Laboratory (GFDL), USA;
- Meteorological Research Institute Coupled Atmosphere-Ocean General Circulation Model (MRI-CGCM 2.2) developed by the Meteorological Research Institute and Meteorological Agency, Japan and;
- Coupled Global Climate Model (CGCM) 3.1 developed by the Canadian Centre for Climate Modeling and Analysis, Canada.

We use these simulated yields results as an input in the ASM to simulate changes in land use. We first estimate the base scenario (without climate change), and then compare baseline results to results under climate change simulated from GCMs in 2050, which reflect the change in crop yields and shifts of crop production patterns as a result of climate change. Due to the uncertainty of factors in the future, we fix all supply side factors to their current level in the base year and only allow the effect of the northward shift of crop production patterns and the change in crop yields. The introduction of change in crop yields and possibility of northward migration of crops cause ASM to change its equilibrium allocation of land use, crop mix, trade flows, commodity prices, production and consumption. Changes in crop acreage are then used to model the resulting response of wetlands and waterfowl in the PPR.

3.1.2 Wetland and Waterfowl Model

We use a simple regression approach to understand the potential effect of climate and land use change on wetlands and waterfowl in the PPR. Our approach is similar in spirit to past models, which have been successfully used to understand the relationship between wetland numbers, weather characteristics, land use and waterfowl populations (see Sorenson et al. 1998; Bethke and Nudds 1995; Johnson and Shaffer 1987). Specifically, we estimate two regression models using historical data. The first model relates pond numbers to climate and land use characteristics:

(1) Ponds = f(precipitation, temperature, land use).

The number of waterfowl that settle in the PPR to breed is largely determined by the availability of wetland habitat. Thus, climate or land use change that affects wetland availability is expected to influence breeding waterfowl populations in the PPR. Previous research has demonstrated the important role of both land use and climate on wetlands in the PPR (see e.g., Voldseth et al. 2007; Johnson et al. 2010).

The second model relates waterfowl populations to pond numbers, land use and harvest:

(2) Ducks = f(ponds, land use, harvest)

While ponds largely influence where waterfowl settle in the PPR, upland land use can reallocate birds on the landscape as females also select landscapes based on the availability of nesting cover. Harvest during the previous hunting season could also influence the number birds in the northward migration, and thus the number of birds that settle in the PPR. This simple set of regression models allows us to relate changes in climate and land use to changes in waterfowl breeding populations. Estimates of breeding population is the primary determinant of waterfowl hunting regulations and is thus one indicator of the potential social impacts of climate induced changes in waterfowl populations.

We use data from a variety of sources to estimate (1) and (2). Pond and waterfowl numbers are from the U.S. Fish and Wildlife Service (USFWS) Waterfowl Breeding Population and Habitat Survey (USFWS 2009). The survey is one of the most extensive, both in time and space, wildlife population and habitat surveys in the world. Since 1955, the USFWS has used aerial surveys to estimate annual pond and waterfowl numbers within temporally consistent survey strata. Six survey strata (41, 45-49) overlap the US PPR (figure 1). We therefore use pond and waterfowl estimates from these six strata to estimate the regression models. For the waterfowl estimates, we use the total count of dabbling ducks, which constitute the largest subgroup of waterfowl that breed in the PPR and the bulk of US harvest.

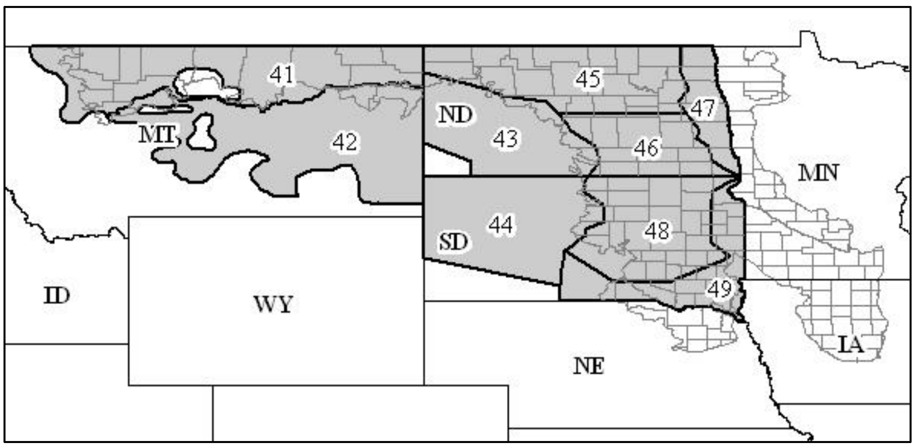

Figure 1. **Waterfowl survey strata in the US Prairie Pothole Region**

Historical land use data is from the National Agricultural Statistics Service (NASS 2010). We aggregate annual county-level estimates of area by crop to the strata-level. To be consistent with the ASM model, we focus on the primary field crops in the PPR (e.g. corn, soybeans, barley, oats, potatoes, sugar beets and wheat). Additionally, since all field crops have similar effects on wetlands and waterfowl nesting habitat, we convert individual crop area to strata-level shares by dividing the total crop area (sum over individual crops) by the total area in each survey strata.

We collect historical precipitation and temperature data from the National Climate Data Center (NOAA 2011). We use data from weather stations distributed across each waterfowl survey strata to estimate average precipitation and temperature at the strata level. Lastly, harvest data comes from the Flyways.us website (http://www.flyways.us/), which is a collaborative effort between waterfowl management agencies to organize data on North American waterfowl. Harvest data is reported annually at the flyway level for the period 1961-2009; we, therefore, use the total harvest for the Central flyway to capture potential harvest impacts on waterfowl breeding populations.

3.2 Linking changes in cropland use to waterfowl

To link the effect of climate change on the agricultural sector to waterfowl response, we use the ASM simulated changes in production of crops as inputs in the regression models described in section 3.1. The change in crop production reflects agricultural reaction to future climate conditions given market mechanisms. This study compares "baseline" scenario in 2007[3] (current condition) with four climate change scenarios in 2050 as discussed in section 3.1.

We first use the ASM to predict regional shifts in cropping patterns due to climate change using yield effects simulated during 2045-2055 provided in Beach et al. (2009) for 63 regions in the US. Although this is a fairly fine level of spatial detail for economic analysis, it is not sufficiently detailed for waterfowl response modeling. Therefore, we used an auxiliary model to downscale ASM results for use in the waterfowl model[4].

We disaggregate the ASM solution of crop acreage to the county level using a county level multi-objective mathematical programming model developed by Atwood et al. (2000), and used in Pattanayak et al. (2005). The Atwood et al. (2000) model was later modified by Attavanich (2011) to better reflect the possibility of crop expansion into new production areas under climate change scenarios[5]. The modified model uses the area of a particular crop allocated to an irrigation status in each county as the primary choice variable. This choice variable is constrained so it matches the land area shift in the ASM, but minimally deviates from the Census of Agriculture, US Bureau of Census, USDA National Resource Inventory (NRI), and USDA county crops data after taking into account the crop migration due to climate change.

The ASM results provide county level estimates of crop area, temperature and precipitation. For projected climate data, we also obtains IPCC SRES scenario A1B[6]'s projected agricultural district level mean temperature and precipitation in the Prairie Pothole Region (PPR) from four GCMs as previously discussed. We then use estimated crop area, temperature and precipitation to simulate wetland and waterfowl numbers under each climate scenario by 1) aggregating county crop area to waterfowl strata-level and calculating crop shares, 2) aggregating mean temperature and precipitation predictions under each climate scenario to waterfowl strata using simple averages, and 3) using the land use and climate data in the estimated pond and duck equations (egn 1 and 2). We use predicted 2007 pond and duck numbers as the baseline for comparison. For the change in the land use share in the baseline, we use change in average crop share between the 1900s and 2000s. Since we do not know how yield levels are likely to change, and since the yield impact is relatively small, we fix yields at the 2000-2009 average for all simulations. Also, since the climate predictions represent the decadal average predicted for 2045-2055, we use the same predicted average temperature and precipitation for all lagged values (i.e., the two-year lagged precipitation and the one-year lagged precipitation are both the predicted average precipitation for each climate scenario). Hence, our predicted changes in pond and duck numbers should be interpreted as averages over the decade not values for any individual future year.

4 Model Results

This section reports our empirical findings from the ASM, wetland and waterfowl model, and simulation of responses of waterfowl populations due to changes in climate and land use in the PPR.

4.1 Results from ASM and its spatial mapping

Table 1 shows acreage of major crops in the PPR under climate change projected from the IPCC scenarios compared to the base scenario. Overall, cropland in the PPR is likely to increase. Considering major crop acreage, corn, soybeans, and hay are projected to increase by 15, 39, and 19 percent, respectively, while acreage of other remaining major crops tends to decrease with wheat projected to have the largest acreage reduction.

Table 1. Acreage of major cropland use (1,000 acres) in the PPR under climate change

	Base	MRI-CGCM 2.2	GFDL 2.0	GFDL 2.1	CGCM 3.1
Major cropland [a] (1,000 acres)					
Barley	2,216	1,438	1,557	1,544	1,510
Corn	19,085	19,961	22,040	21,904	20,614
Oats	513	372	438	371	383
Wheat	14,336	10,517	9,945	10,384	10,492
Hay	5,104	7,119	6,925	6,821	6,885
Silage	800	751	742	1,275	795
Soybeans	15,346	18,275	16,657	15,715	17,652
Sugarbeets	710	398	437	404	436

Note: [a] Crop acreage in the PPR is calculated by breaking down results of ASM crop acreage into the county level and reaggregating to the PPR level using spatial mapping approach discussed in section 3.2.

Because climate-induced shifts in crop production patterns are expected to significantly influence the productivity of the PPR for waterfowl, understanding changes in movements and distributions of cropland[7] under climate change is important. Our study provides such information. Figure 2 shows the estimated percent change of county-level crop shares[8] from the base scenario under climate change in 2050 from the four GCM scenarios in the PPR. In all scenarios, small percent changes in crop share are found in almost all Iowa counties. Conversely, a majority of GCMs project that areas in the eastern section of North Dakota, the western section of South Dakota, and the central to northern section of Minnesota will have a large increase in crop share, which potentially reduces waterfowl productivity. On the other hand, a large reduction of crop share is likely detected in the southern section of Minnesota and the central to southern part of South Dakota, which could benefit waterfowl.

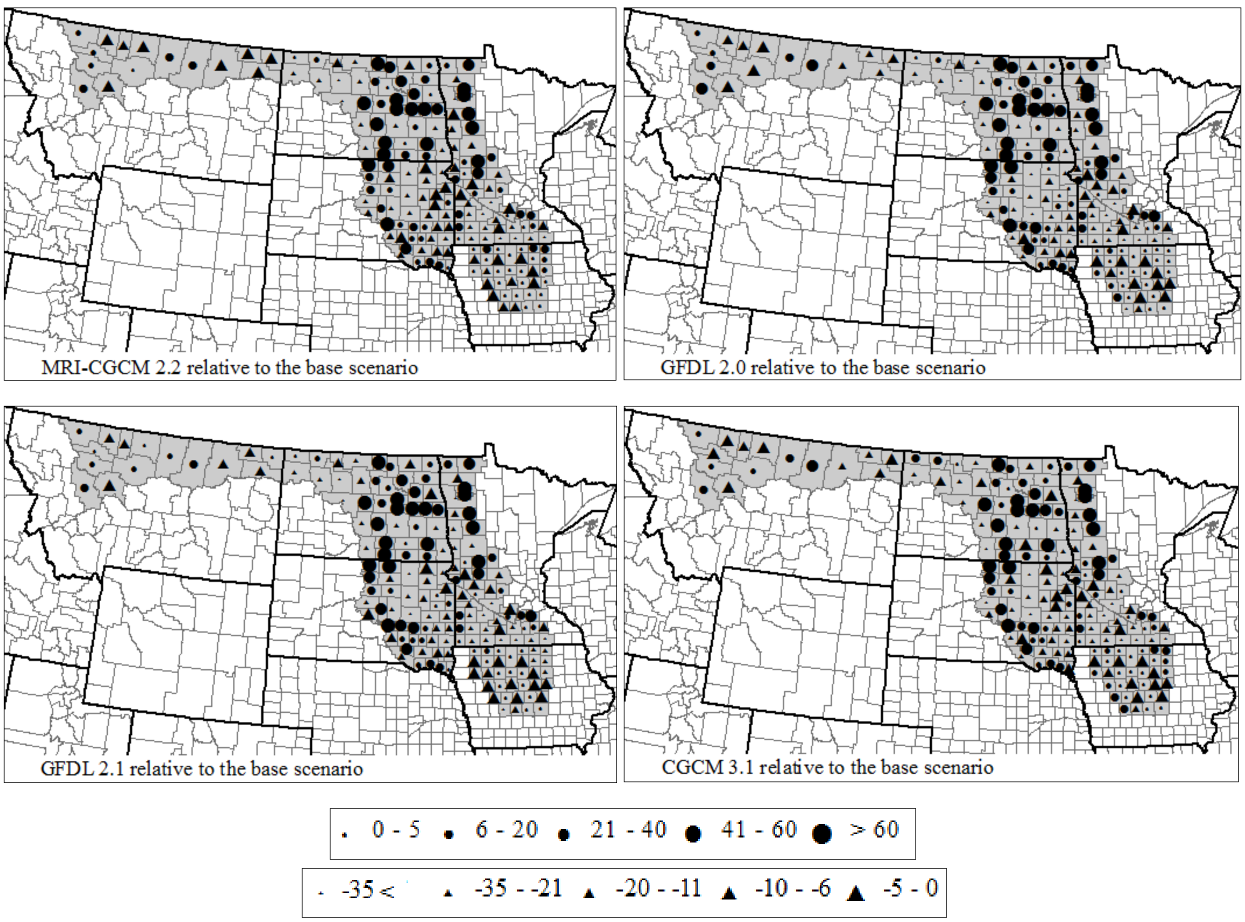

Figure 2. Estimated percent change of county-level crop share from the base scenario under climate change in 2050 from GCM scenarios in the PPR

4.2 Results from wetland and waterfowl model

We use the data described in section 3.1.2 to estimate (1) and (2). For each equation we use a log-linear specification, and a one-way fixed effects model to capture unobserved cross-sectional heterogeneity[9]. In the pond equation (1), we include temperature (T) one- and two-year lags for precipitation (P) because prairie wetlands are dependent on accumulated soil moisture (Sorenson et al. 1998), and the change in the crop share (ΔCS) as changes in crop area better capture potential wetland loss. In the duck equation (2), we include the current year and one-year lag of ponds, the crop share and the lagged harvest (H) since birds are harvested in the fall and thus affect the following spring migration. The regressions fit the data well with R^2 of 0.75 and 0.83 for the pond and waterfowl models, respectively, and highly significant F-statistics. The estimated equations, with fixed effects omitted for simplicity and p-values in parentheses, are:

$$\underset{}{ln(\text{Ponds})} = \underset{(<0.0001)}{13.76} - \underset{(0.01)}{0.04}*T + \underset{(0.85)}{0.01}*P + \underset{(0.018)}{0.09}*P_{t-1} + \underset{(0.0001)}{0.14}*P_{t-2} - \underset{(0.06)}{1.49}*\Delta CS \tag{3}$$

$$ln(\text{Ducks}) = \underset{(<0.0001)}{12.25} + \underset{(<0.0001)}{0.000003}*\text{Ponds} + \underset{(0.013)}{0.000001}*\text{Ponds}_{t-1} - \underset{(0.048)}{1.34}*CS + \underset{(0.073)}{0.00000008}*H \tag{4}$$

Parameter estimates generally have the expected sign and reasonable magnitudes. Higher average temperatures, lower average precipitation and higher shares of land in crops decrease pond numbers. Similarly, higher pond numbers and lower crops shares are correlated with high duck numbers. Harvest has a very small and positive effect on duck numbers. This seemingly counterintuitive result is consistent with the theory that harvest is compensatory (i.e., increased survival rates compensate for harvest). The estimate on harvest essentially implies that every harvested duck is perfectly compensated for through increased production. The estimated models allow us to predict impacts on waterfowl, given a climate scenario and predicted land use from the ASM model.

4.3 Effects of climate and land use change on waterfowl populations in the PPR

Our results suggest that climate change and its induced land use changes will have dramatic impacts on waterfowl in the PPR; however, the impacts vary substantially by climate scenario (figure 3). Under three of the four climate scenarios pond and wetland numbers decrease substantially, with a worst case scenario reduction in duck numbers of 25% from the 2007 baseline. For the GFDL 2.0 climate scenario, however, our results suggest an increase in ponds (9%) and thus duck populations (4%).

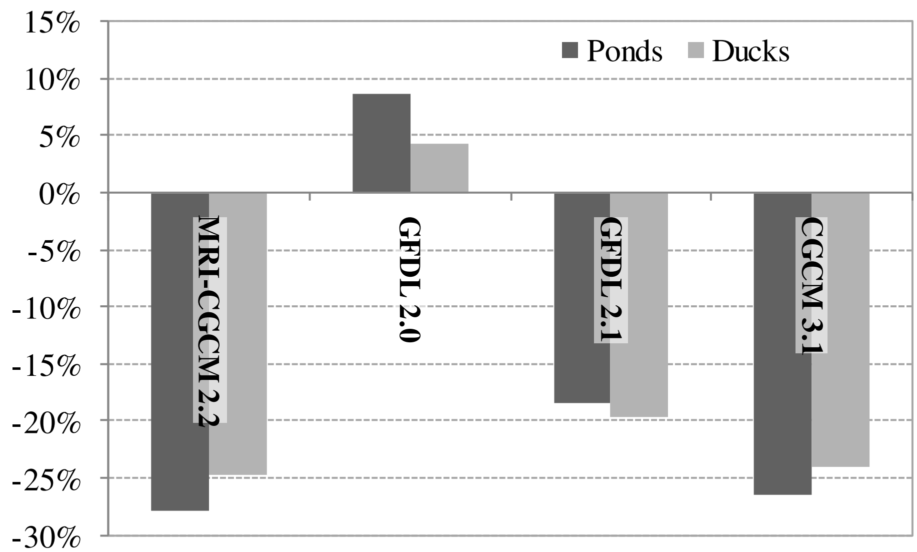

Figure 3. Percent change in pond and duck number relative to 2007 baseline under four alternative climate scenarios.

Differences across scenarios are largely explained by differences in temperature and precipitation predictions. The GFDL 2.0 scenario includes minor increases in temperature accompanied by significant increases in precipitation (1", approximately 25%, on average across strata). The increases in precipitation are sufficient to offset any negative impacts of temperature or land use change on pond numbers. The GFDL 2.1 scenario also has increased precipitation (0.2" on average); however, the increase in temperature predicted in this scenario (2.3°F on average) is sufficient to cause large decreases in pond and duck numbers. The most extreme scenarios, CGCM 3.1 and MRI-CGCM 2.2, predict small decreases in precipitation combined with increases in temperature (2-3°F on average). This combination results in substantial reduction in pond and duck numbers.

The impacts of climate change on pond and duck numbers, however, are not completely explained by precipitation and temperature. Land use change plays an important role. The ASM model generally predicts an increase in corn and soybeans acreage, and a decrease in wheat acreage in the PPR. The reduction in wheat and other minor crops can be accompanied by increases in pasture or other major crops especially corn and soybeans. Although increases in pasture, which can be suitable waterfowl habitat, should be positive for waterfowl, the net effect of land use change implies an increase in the share of land in crops in most waterfowl strata under most climate scenarios. Land use response to climate change therefore generally exacerbates the negative effects of climate change on duck populations.

The extent of land use change impacts is best demonstrated by considering temperature and precipitation impacts absent of land use change. We thus predict pond and duck numbers assuming that crop shares remain at baseline levels. For the three scenarios under which climate change reduces pond and duck numbers, ignoring land use change would lead to a significant underestimate of climate change impacts (table 2). Not accounting for land use response leads to underestimating ponds and ducks by as much as 14% and 10%, respectively. This implies underestimating the effect of climate change on duck populations by nearly 300,000 birds, approximately 10% of the average current harvest.

Table 2. Comparison of pond and duck prediction under climate change, with and without land use response

	Percent Change from Baseline			
	With Land Use Change		Without Land Use Change	
	Ponds	Ducks	Ponds	Ducks
MRI-CGCM 2.2	-28%	-25%	-17%	-15%
GFDL 2.1	-19%	-20%	-5%	-16%
CGCM 3.1	-26%	-24%	-16%	-22%

Although climate change and the associated land use response are likely to have significant impacts on ducks in the PPR, the impacts are not uniformly distributed over space. Predicted temperatures and precipitation under alternative climate scenarios differ by waterfowl strata. Thus, even with our highly aggregated strata-level data, land use response and the ultimate impact on ponds and ducks have spatial variation that could be important for targeting programs to mitigate climate impacts.

Regardless of climate scenario, the Montana portion of the PPR (strata 41) is predicted to gain ducks with climate change. This region has historically been a relatively low duck production area because it receives less rainfall than regions to the east and south. It also has the lowest crop share of any strata. With climate change the region is predicted to gain precipitation and have relatively little change in the share of land in crops. Thus, the region could see increased pond numbers with little loss in waterfowl nesting habitat (figure 4).

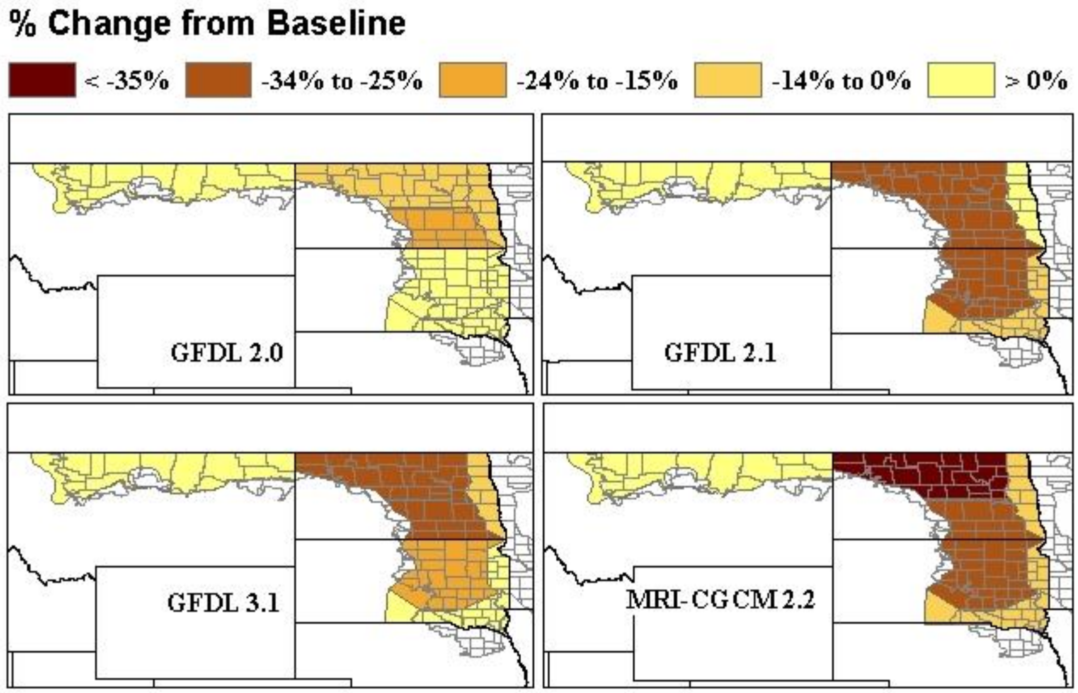

Figure 4. Percent change in duck populations from baseline by waterfowl survey strata under alternative climate scenarios.

The central portion of the PPR is predicted to see the largest negative impacts to duck populations. In all climate scenarios the strata's in eastern North and South Dakota lose significant portions of their current duck populations. These strata currently produce the most ducks (78%) because they have relatively high pond numbers and, related, significant land area not in crop production (> 50%). With climate change, these strata are predicted to experience small to no increase in precipitation, significant temperature increases, and the largest relative increases in crop land area. As a result, this traditionally productive waterfowl region will have fewer ponds, less nesting habitat and, as a result, significantly fewer ducks.

In contrast, the strata in eastern and southern North and South Dakota are predicted to have very modest gains or losses in duck populations across climate scenarios. Here, the explanation is largely unrelated to climate change factors. These regions are currently dominated by intensive crop production (> 60%), and, as a result, have relatively low pond numbers. They, therefore, have not attracted many breeding ducks in recent history. The changes in temperature, precipitation and land use predicted under alternative climate scenarios are not substantial enough to significantly change, in either direction, the waterfowl potential of these regions.

5 Concluding Remarks

This study examines the joint effect of climate change and the resulting land use response on waterfowl production in the Prairie Pothole Regions (PPR) by linking a model of land use changes induced by climate change with a wildlife habitat and productivity model. Our results reveal that overall cropland in the PPR is likely to increase, but changes vary spatially across the region. In all the climate scenarios, small percent changes in crop share are found in almost all of counties in the Iowa part of the PPR. A majority of climate scenarios project that areas in the eastern section of North Dakota, the western section of South Dakota, and the central to northern section of Minnesota are generally predicted to have a large increase in crop share. On the other hand, a large reduction of crop share is likely detected in the southern section of Minnesota and the central to southern part of South Dakota.

Using the estimates from the climate, wetlands and waterfowl productivity models, we also find that 1) higher average temperatures, lower average precipitation and higher shares of land in crops relative to pasture decrease pond numbers; 2) lower pond numbers and higher crop shares are correlated with lower duck numbers and; 3) yield increase have a very small and positive effect on duck numbers. In addition, when we include alternative climate scenarios and their effects on crop mixes, we find that pond and wetland numbers decrease substantially, with a worst case scenario reduction in duck numbers of 25% from the 2007 baseline. For the GFDL 2.0 climate scenario, however, our results suggest an increase in ponds (9%) and thus duck populations (4%). The study also finds that land use response to climate change generally exacerbates the negative effects of climate change on duck populations.

The spatial heterogeneity in climate effects could pose serious challenges to waterfowl conservation efforts targeted towards climate mitigation. Investments could, for example, be targeted towards securing habitat in Montana. These investments could further bolster the predicted increases in duck production given climate change. The Montana region, however, has historically produced a very small proportion of the regions ducks. Moreover, even with the predicted improvements with climate change, this region does not produce nearly enough additional ducks to offset those lost in other regions. In the three climate scenarios that reduce duck populations, for example, removing all land from crop production in the Montana portion of the PPR only offsets 5% of the duck losses in the rest of the PPR.

This suggests that conservation investments will have to be focused in the central or eastern portion of the PPR to have any chance of significantly mitigating climate effects. These regions, however, have high historic shares of land in crops and/or are predicted to gain significant crop shares under alternative climate scenarios. Land in these regions is therefore likely to be more highly valued. Thus, conservation efforts will have to compete with agriculture to secure wetland and nesting habitat. Given the duck deficits predicted under several climate scenarios, limited conservation budgets will likely be challenged to conserve the amount of area required to mitigate climate change impacts. Conservation programs will therefore need to be strategically targeted to maximize cost effectiveness (see e.g., Rashford and Adams 2007).

Appendix

Table A1. ASM regions and subregions

Market Region	Production Region (States/Subregions)
Northeast (NE)	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
Lake States (LS)	Michigan, Minnesota, Wisconsin
Corn Belt (CB)	All regions in Illinois, Indiana, Iowa, Missouri, Ohio (IllinoisN, IllinoisS, IndianaN, IndianaS, IowaW, IowaCent, IowaNE, IowaS, OhioNW, OhioS, OhioNE)
Great Plains (GP)	Kansas, Nebraska, North Dakota, South Dakota
Southeast (SE)	Virginia, North Carolina, South Carolina, Georgia, Florida
South Central (SC)	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Tennessee, Eastern Texas
Southwest (SW)	Oklahoma, All of Texas but the Eastern Part (Texas High Plains, Texas Rolling Plains, Texas Central Blacklands, Texas Edwards Plateau, Texas Coastal Bend, Texas South, Texas Trans Pecos)
Rocky Mountains (RM)	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
Pacific Southwest (PSW)	All regions in California (CaliforniaN, CaliforniaS)
Pacific Northwest (PNW)	Oregon and Washington, east of the Cascade mountain range

Source: Attavanich and McCarl, 2011

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End Notes

[1] Their studied crops are barley, corn, cotton, forage production, oats, peanuts, potatoes, rice, rye, sorghum, soybeans, sugarbeets, tomatoes, and wheat.
[2] It is common practice in climate change analysis to use several GCM projections to reflect the uncertainty inherent in such projections.
[3] We adjust the base year used in ASM from 2005 to 2007 to reflect empirical evidences from the latest Agricultural Census.

[4] Development of a county-level counterpart to the ASM crop mix would not be necessary if we could use county as the ASM spatial specification. However, not only would such a model be very large but developing/maintaining production budget, crop mix and resource data for such a scale would be a monumental undertaking. Thus, we run ASM at a more aggregate level and reduce the solution crop mixes to the county level.
[5] The regionalizing downscaling of Atwood et al. (2000) disaggregated the solution of crop mixes and crop acreage from sector model to the county level by fixing crop mix and crop acreage solutions close to the county level historical crop mix, which cannot fully account for items which are expected to fall significantly outside the range of historical observation.
[6] Scenario A1B most closely reproduces the actual emissions trajectories during the period since the SRES scenarios were completed (2000-2008). It is reasonable to focus on A1B scenario group versus those in the B1 and B2 scenario groups that have lower emissions projections because in recent years actual emissions have been above the A1B scenario projections. At the same time, there has been considerable interest and policy development to encourage non-fossil fuel energy, which is consistent with the A1B scenario vs. A1F1 or A2 that assume a heavier future reliance on fossil fuels (Beach et al. 2009).
[7] Cropland use in figure 2 is the summation of acreage of major crops in the PPR including barley, corn, oats, wheat, hay, silage, soybeans, and sugarbeets covering about 95 percent of total crop acreage in the PPR in 2007.
[8] Crop share is calculated by dividing the county-level acreage of total major cropland use (sum over individual crops) by the total land area in that county.
[9] We experimented with running the model as a system and with correcting for autocorrelation and heteroskedasticity (i.e., Parks method). Since our primary purpose is prediction and none of the alternative regression approaches produced meaningfully different predictions, we report and use estimates from the simple model.