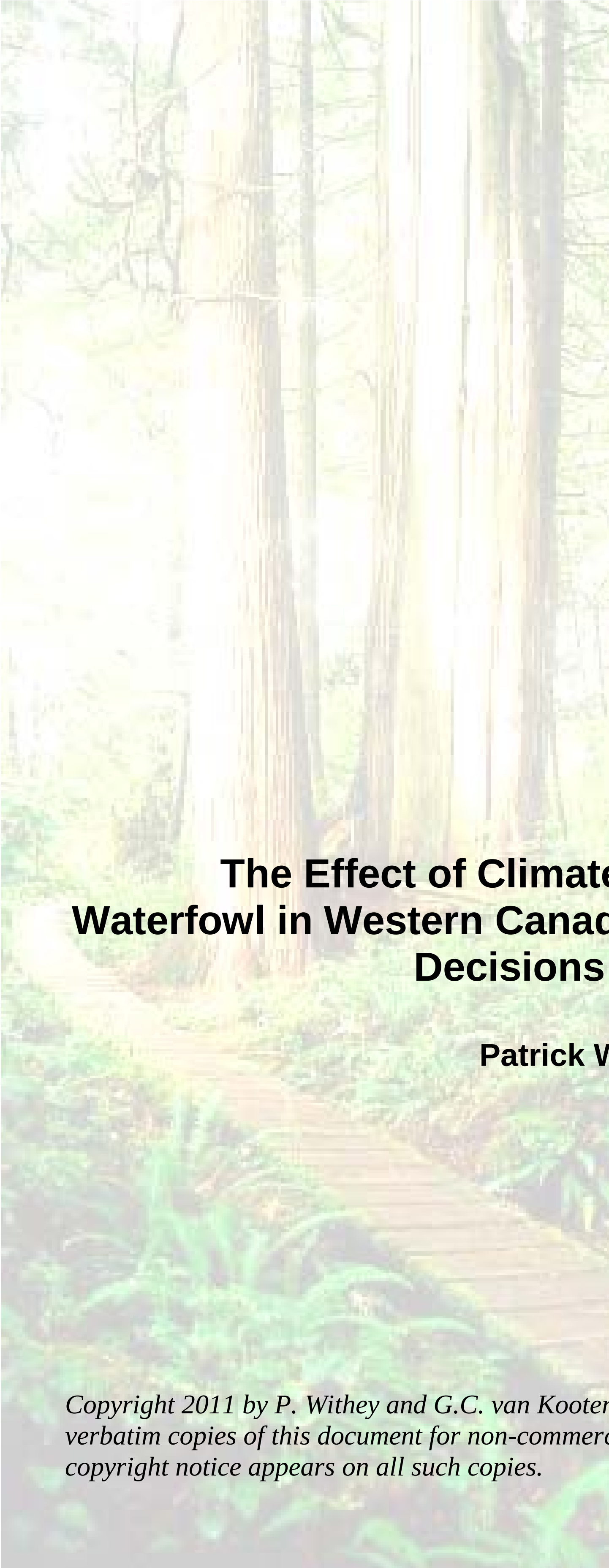

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The Effect of Climate Change on Wetlands and Waterfowl in Western Canada: Incorporating Cropping Decisions into a Bioeconomic Model

Patrick Withey and G. Cornelis van Kooten

November 2011

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The Effect of Climate Change on Wetlands and Waterfowl in Western Canada: Incorporating Cropping Decisions into a Bioeconomic Model

Patrick Withey
(e-mail: pwithey@uvic.ca)

and

G. Cornelis van Kooten
(e-mail: kooten@uvic.ca)

Department of Economics
University of Victoria
PO Box 1700, Stn CSC
Victoria, Canada V8W 2Y2

ABSTRACT

We extend an earlier bioeconomic model of optimal duck harvest and wetland retention in the Prairie Pothole Region of Western Canada to include cropping decisions. Instead of a single state equation, the model has two state equations representing the population dynamics of ducks and the amount of wetlands. We use the model to estimate the impact of climate change on wetlands and waterfowl, including direct climate effects as well as land use change due to biofuel policies aimed at mitigating climate change. The model predicts that climate change will reduce wetlands by 47-56 percent from historic levels. Land use change is expected to reduce wetlands by 45 percent from historic levels, whereas direct climate effects will range from a reduction of 2-11 percent, depending on the future climate scenario. This result indicates that models that neglect the effect of land use change underestimate the effect of climate change on wetlands. Further, wetlands loss is geographically heterogeneous, with losses being the largest in Saskatchewan.

Keywords: bioeconomic modeling; wetland protection; wildlife management; climate change; biofuels

JEL Classification: Q57, C61, Q25, Q54, C13, Q10, Q16

1. INTRODUCTION

Climate change could pose a serious threat to the future of wetlands and the services they provide. Currently, the Canadian prairie pothole region (PPR) is one of the world's most productive waterfowl breeding grounds, but a warmer and drier climate could negatively impact its ability to produce waterfowl (Johnson et al. 2005). A reduction in wetlands area would subsequently lead to the loss of other significant social benefits that come from wetlands in the PPR, such as water filtration, viewscapes and storage of greenhouse gases. It is impossible to know with certainly the climate conditions that will prevail in the next century, but IPCC (2007) climate predictions for the region indicate that air temperatures could rise by between 1.8^{o}C and 4.0^{o}C by 2100, while average annual precipitation might vary between a decrease of 5% and an increase of 10%. A warmer and potentially drier climate has important implications for wetlands management.

In addition to direct climate effects, policies that seek to mitigate climate change, such as those that subsidize the production of biofuel crops, will decrease the value of wetlands relative to agricultural land, thereby adversely impacting wetlands and the waterfowl that they support.

Given that, in the PPR, significant use and non-use benefits are derived from wetlands and the waterfowl they produce (van Kooten et al. 2011), it is important that these benefits be considered in any analysis regarding the retention of wetlands. It is also important to understand how climate change might impact wetlands, and how decisions to manage wetlands are affected by climate change and climate policy. Given uncertainty about future precipitation in the region, it is important to consider the effects of both a drier and wetter climate on wetlands and waterfowl management decisions. The objectives of the current research are therefore as follows:

- to develop an optimal control model of wetland and waterfowl management that includes cropping decisions while keeping in mind amenity values of wetlands, and to use the model to estimate the effect of climate change on current levels of wetlands;
- to investigate the possible effect that projected future precipitation will have on wetlands in Canada's PPR; and
- to examine the impact that climate mitigation policies, particularly incentives to increase cropland area devoted to production of biofuels, will have on wetlands.

Despite the value of, and threats to, wetlands, bioeconomic models to date have treated wetlands as the decision variable rather than as a state variable – as if the decision maker can directly choose an optimal amount of wetlands. In the current research, we treat wetland area as a state variable and cropping decisions as the control variable impacting wetlands. The advantage of this approach is that the effects of a drier climate and biofuel policies can be modeled explicitly. We extend a bioeconomic waterfowl hunting model to include cropping decisions, and solve for steady state levels of ducks, duck harvests by hunters, wetland area and cultivated area. Given baseline (historic) values, we can estimate the impact of climate change and policies to mitigate it (i.e., incentives to increase biofuel production) on these variables.

A further contribution of the current research is that we determine the impacts of climate change at both the supra-regional and sub-region levels. This is done by solving our model for the entire region, and then re-parameterizing and solving it for (i) each of the Prairie Provinces and (ii) each of the 15 strata that make up the PPR, as defined by the U.S. Fish and Wildlife Service (2010). By solving the regional models separately, we are able to determine how climate change effects on wetlands differ among regions in the PPR and how this impacts optimal wetlands management plans.

When calibrated to solve for historic values of wetlands, the model predicts that the shadow value of wetlands is much higher than the return to cropping. This indicates that too few wetlands have historically been retained in the PPR. Further, the effect of climate change is that the optimal level of wetlands to retain falls by as much as 47 to 56 percent from baseline values, depending upon the climate scenario. At the sub-region level, the effect of climate change on wetlands management is most pronounced in the province of Saskatchewan.

2. BACKGROUND LITERATURE

Mathematical bioeconomic models are used to efficiently allocate renewable natural resources subject to ecological constraints. Many studies have looked at the optimal management of wildlife in a variety of settings, with models ranging from the analytic to numeric, from deterministic to stochastic, and from static to dynamic, but, in this section, we only provide a brief review of studies of direct relevance to migratory waterfowl and the study region.

Gardner Brown and his colleagues (Brown and Hammack 1973; Hammack and Brown 1974; Brown et al. 1976) were the first to use mathematical bioeconomic models to address wetlands conservation in the context of migratory waterfowl in North

America. They specified a discrete bioeconomic optimal control model of duck hunting that maximizes benefits to hunters minus the costs of providing wetlands. The objective function is constrained by waterfowl population growth. The authors solved for the optimal values of wetlands, waterfowl and harvest. Their focus, however, was solely on duck hunting values, ignoring other waterfowl values and wetland benefits.

Van Kooten et al. (2011) updated and re-parameterized the foregoing model, extending it to include the amenity values of both ducks and wetlands. Upon solving for the optimal levels of ducks, harvests and wetlands, these authors confirmed the original results of Brown and his colleagues. Withey and van Kooten (2011) then extended the van Kooten et al. (2011) model to consider the impact of climate change on wetlands management, but they ignored the impact of climate mitigation policies on cropping decisions and wetlands conversion. In this paper, therefore, we further extend the above models to include cropping decisions in the objective function and wetlands as a state variable, thereby allowing us to estimate the combined effect of climate change and climate-change related policies on wetlands retention.

In this regard, a relevant study by Miettinen and Huhtala (2005) specified an optimal control model of cereal crop production and grey partridge hunting values in Finland. Like the current study, the researchers maximized returns to land used for crops as well as land that is conducive for bird habitat, subject to constraints on the grey partridge population. However, there are several differences between our study and theirs. First, we include amenity values of birds and wetlands, and solve for actual steady-state values for each of ducks, wetlands and harvests. Second, we include a separate state equation for waterfowl habitat that allows us to model explicitly the effect of climate change on waterfowl.

Other relevant studies have estimated the impact of climate change on wetlands, with several having used a multiple regression approach to estimate the impact of climate measures on wetlands in parts of the PPR (Larson 1995; Sorenson et al 1998). A detailed review of this literature can be found in Withey and van Kooten (2011). The current study advances these studies in several ways. First, we estimate the optimal management of wetlands and waterfowl in the face of climate change. Second, we estimate both direct climate effects as well as effects related to increased biofuel production.

3. ANALYTIC MODEL

In this section, we present an optimal control model of agricultural grain production and duck harvesting in the prairie pothole region. Our motivation is to develop a model to determine the total effects of climate change on wetlands and waterfowl management. Our bioeconomic model incorporates amenity values of both ducks and wetlands, and takes into account the ability of wetlands to sequester carbon dioxide and methane. A model that seeks to capture the effects of climate change on wetlands should include the climate change mitigation benefits that wetlands provide.

The objective of the social planner is to maximize the private net returns to crop production plus the public net benefits of harvesting ducks, keeping in mind the benefits of both wetlands and waterfowl. Duck harvests and area cropped constitute the control variables, which are constrained by the number of ducks and wetlands, respectively.

The objective function of the social planner can be written as:

$$\sum_{t=0}^{T}\left[v(h_t)+\alpha D_t + B(W_t) - C(W_t) + N(a_t)\right]\rho^t , \qquad (1)$$

where $v(h_t)$ is a function describing the benefits derived from harvesting h_t ducks at time t; D_t refers to the population of ducks at t; and $B(W_t)$ and $C(W_t)$ are the respective annual benefits and costs of providing W_t wetlands at time t. The marginal ecosystem benefit function is assumed to have the following properties: $\partial B/\partial W_t > 0$ and $\partial^2 B/\partial W_t^2 \leq 0$; α is the amenity value of an additional duck, which we assume is a positive constant; and $N(a_t)$ is the net return to cropping area a_t (\$/acre). Cropped land a_t that is not considered suitable as waterfowl habitat includes all land in pasture, summerfallow and crops. While some of this land may be used as waterfowl habitat, studies show that ducks have relatively low breeding success in areas planted to crops in the spring or kept in summer fallow (Devries et al. 2008). While fall planted winter wheat area provides much better nesting habitat for waterfowl, the area planted annually is quite small relative to spring crops and can thus be ignored. Finally, $\rho = 1/(1+r)$ is the discount factor, with r the social discount rate, and T is the length of the planning horizon, which could be infinite.

Equation (1) is maximized subject to a bioeconomic constraint describing the duck population dynamics and another describing the change in wetlands. First, ducks breed in the PPR in May and begin the fall flight south in September, which is also the start of hunting season. The fall flight consists of the fraction s_1 of May breeding ducks D_t that survive to September, plus offspring that survive to September. The latter is given by the recruitment function $g(D_t, W_t)$. In the fall, h_t ducks are harvested, and the remaining ducks represent the winter population. Of this, s_2 ducks will survive and return in the spring to breed. The population dynamics for ducks are represented by the following equation:

$$D_{t+1} = s_2 [s_1 D_t + g(D_t, W_t) - \pi h_t]; \qquad (2)$$

$$D_t, h_t, W_t \geq 0; \text{ and } D_0 > 0, W_0 > 0 \text{ given}; \qquad (3)$$

where D_{t+1} is the number of mature ducks returning to the prairie pothole breeding grounds in year $t+1$, s_1 is defined above, s_2 is the fraction of mature ducks that are not killed by hunters and survive to return to the breeding grounds in year $t+1$, and $\pi > 1$ accounts for the loss of ducks that are killed or maimed by hunters but not collected or reported. Conditions (3) are non-negativity requirements and initial conditions regarding the numbers of ducks and ponds.

Wetlands are needed to produce ducks, which provide amenity and duck hunting benefits. Wetland habitat is positively correlated with previous levels of wetlands and negatively impacted by a drier climate and agricultural policies that drain wetlands for crop production. Therefore, the following constraints describe the evolution of wetlands:

$$W_{t+1} = \beta_0 + \beta_1 W_t \, e^{SPI_t}, \qquad (4)$$

$$\overline{A} = W_t + a_t, \qquad (5)$$

$$W_t, a_t \geq 0; a_0, W_0, SPI_0 \text{ given}; \qquad (6)$$

where a_t refers to the cultivated area in period t. Wetlands in a given period are a function of wetlands in the preceding period and climate. As a measure of climate and climate change, we use the standardized precipitation index (*SPI*), which is in fact a drought index. The total land area available at any given time is denoted $\bar{A}$, and this land can be in wetlands (including undeveloped uplands habitat) or cropland (including pasture and summer fallow). We ignore factors that might result in the conversion of unimproved forest and range land into agriculture, as this occurs at the extensive margin; our interest here is the intensive margin, where wetlands in the agricultural zone are being converted to cropland. A discussion of intensive and extensive margins in found in van Kooten and Bulte (2000, pp.59-73). We hypothesize that changes in wetland area are impacted by climate and the conversion of land to cropland. Finally, the β_is are parameters to be estimated.

The Lagrangian associated with the above bioeconomic problem is:

$$L = \sum_{t=0}^{T} \rho^t \left\{ \left[v(h_t) + \alpha\, D_t + B(W_t) - C(W_t) + N(a_t) \right] + \theta_t (\bar{A} - W_t - a_t) \right\} + \left\{ \begin{array}{l} \lambda_{t+1}^{D} \left[(s_1 s_2 - 1) D_t + s_2 g(D_t, W_t) - s_2 \pi h_t + D_t - D_{t+1} \right] \\ + \lambda_{t+1}^{W} \left[\left(\beta_0 + W_t (\beta_1 e^{SPI_t} - 1) + W_t - W_{t+1} \right) \right] \end{array} \right\} \rho^{t+1} \quad (7)$$

where L is the Lagrange function, and λ^D_{t+1} and λ^W_{t+1} are the shadow prices of an additional duck and wetland acre, respectively. Equation (7) can be solved by finding the first-order conditions for each control and state variable in each of T periods, that is by setting $\partial L/\partial h_t = 0$, $\partial L/\partial a_t = 0$, $\partial L/\partial D_t = 0$ and $\partial L/\partial W_t = 0$. One also needs to take into account the constraint equations, which can be recovered from (7) through differentiation as follows: $\frac{\partial L}{\partial \lambda^i{}_{t+1}} = 0$ and $\frac{\partial L}{\partial \theta_t} = 0$.

Assuming an interior solution, the first-order conditions are as follows:

$$\frac{\partial L}{\partial h_t} = v'(h_t) - \rho\lambda_{t+1}^{D}\pi s_2 = 0 \tag{8}$$

$$\frac{\partial L}{\partial a_t} = N'(a_t) - \theta_t = 0 \tag{9}$$

$$\frac{\partial L}{\partial D_t} = \alpha + \rho\lambda_{t+1}^{D}\left[(s_1 s_2 - 1) + s_2\frac{\partial g}{\partial D_t})\right] + \rho\lambda_{t+1}^{D} - \lambda_t^{D} = 0 \tag{10}$$

$$\frac{\partial L}{\partial W_t} = (B - c) + s_2\rho\lambda_{t+1}^{D}\frac{\partial g}{\partial W_t} + \rho\lambda_{t+1}^{W}(\beta_1 e^{SPI_t} - 1) - \theta_t + \rho\lambda_{t+1}^{W} - \lambda_t^{W} = 0 \tag{11}$$

Differentiating with respect to the Lagrange multipliers yields the state equations (2), (4) and (5). For convenience we assume $C'(W_t) = c$, a constant, which is the annual cost of providing an additional pond; and $dN/da_t = N'(a_t)$ is the marginal net revenue from cropping the next acre taken out of wetlands.

From maximum principle (8), $(1/\pi)\,\partial v/\partial h_t = \rho\,\lambda^{D}_{t+1}\,s_2$, which says that hunting should continue until the value of the marginal duck that is harvested (adjusted for the fact that not all birds killed are recovered) equals the user cost of taking that bird. The user cost equals the discounted shadow value of leaving the duck in situ adjusted for the fact that not all unharvested ducks survive to breed the following spring.

Maximum principle (9), $N'(a_t) = \theta_t$, says that farmers should continue to crop to the point where the marginal revenue of the last acre equals the shadow value of adding another acre to the total land base (i.e., at the extensive margin). In the current model, this value is equal to the value of land that is not currently cropped, but which will be put into crop production should crop prices rise ever so slightly.

Equations (10) and (11) are dynamic arbitrage conditions. Condition (10), that

$\rho\lambda^D_{t+1}(s_1 s_2 + s_2 \frac{\partial g}{\partial D_t})) = \lambda^D_t - \alpha$, requires hunters to take into account the value of allowing some ducks to escape so they can breed and produce more birds that are then available to future hunters and viewers. The discounted future (shadow) value of allowing a duck to escape (adjusted for mortality and the marginal growth in duck population) must equal the current (shadow) value of harvesting that duck less the amenity value of the duck.

Similarly, condition (11), that $\rho\left[s_2\lambda^D_{t+1}\frac{\partial g}{\partial W_t} + \lambda^W_{t+1}\beta_1 e^{SPI_t}\right] = \lambda^W_t + (c - B + \theta_t)$, requires that consideration be given to the future value of wetland retention when deciding on whether to drain an additional wetland for agricultural use. That is, decision makers must retain (or drain) wetlands so that the current value of a wetland, as given by the shadow value of the wetland less the net (opportunity) cost of retaining it, is equal to the future discounted value of the marginal wetland. The latter is determined by the future value of wetlands in the production of ducks plus the actual future shadow value of the wetland in providing amenities to society.

A steady-state solution is found by letting $\lambda^W_{t+1} = \lambda^W_t$, $D_{t+1} = D_t$, $\lambda^D_{t+1} = \lambda^D_t$ and $W_{t+1} = W_t$, $\forall\, t$. We then find the following seven steady-state conditions from equations (2), (4), (5) and (8) through (11):

$W = \beta_0/(1 - \beta_1 e^{SPI_t})$; (12)

$a = \bar{A} - W$; (13)

$\theta = N'(a)$; (14)

$$D = s_2\,[s_1 D + g(D, W) - \pi h]; \tag{15}$$

$$2 - \rho - s_1 s_2 = \frac{\alpha \pi s_2}{v'(h)} + s_2 \frac{\partial g}{\partial D}; \tag{16}$$

$$\lambda^W = \frac{B - c - \theta + \dfrac{v'(h)}{\pi s_2} s_2 \dfrac{\partial g}{\partial W}}{1 - \rho \beta_1 e^{SPI}}; \tag{17}$$

$$\lambda^D = \frac{v'(h\ )}{\rho \pi s_2} \tag{18}$$

Once functional forms and associated parameters are estimated for $N(.)$, $v(.)$, $g(.)$ and B_i and the parameters s_1, s_2, ρ (or discount rate r), α, c, $B(W)$ and π are determined, the model can be solved for the optimal waterfowl population, level of wetlands, and decisions concerning harvests and agricultural cropping that maximize the planner's well being. Further, we can find the shadow price of ducks and wetlands. The seven equations are used to solve for the seven unknowns, W, D, h, a, λ^D, λ^W *and* θ.

By design, the base-case steady-state level of wetlands will roughly equal historic values, while waterfowl populations will be higher than historic values, given the amenity value of ducks and the value of duck harvests. The relative value of wetlands to cropland (at historic levels of wetlands) will be determined by the shadow value of wetlands. We estimate climate change impacts on wetlands via the SPI variable or change in land use in equation (13).

4. PARAMETERIZATION AND RESULTS

We parameterize and solve the preceding analytical model for Canada's entire PPR, as well as for disaggregated regions of the PPR. This creates a bit of a dilemma, however, because optimal duck harvests are determined at the supra-regional level and not the sub-region or provincial level. The problem cannot be addressed simply by imposing the supra-regional optimal harvests on the regions because there is no straightforward way to allocate the entire harvest to a sub-region. Our approach, therefore, is to examine the allocation *ex post*. If the sum of the (optimal) sub-region level harvests are 'close' to optimal overall harvest, we can be confident of the general robustness of our model.

We first consider parameter values that calibrate the model to the entire PPR and solve for the associated steady-state solution. We then parameterize the sub-region models and solve for the steady-state levels of wetlands and duck harvests for each.

Entire Region Results

Given lack of information about the demand function for duck hunting, we adapt and update Brown and Hammack's (1973) function to obtain the following valuation function (van Kooten et al. 2011): $v(h) = 114.580\ h^{0.409}$. Net revenue from cropping is then calibrated for all crops over the entire PPR using data from Statistics Canada. Data on total revenues and costs from crops are available from Cansim Table 20044, and are divided by the number of acres seeded from Cansim Table 10017 to get estimates on a dollar per acre ($/ac) basis for 2008. For the entire region, respective revenues and costs are $81 per acre (ac) and $39/ac, resulting in net revenue of $42/ac.

Estimates of the annual marginal environmental service and other amenity benefits of wetlands are based primarily on meta-regression analyses by Woodward and Wui (2001) and Brander et al. (2006). Estimates of these benefits range from $9 to $77 per acre; for simplicity, we assume a constant marginal benefit of $45 per acre. The annualized restoration cost plus opportunity cost of retaining the marginal wetland is determined using data from Cortus et al. (2011) and Hansen (2009), and ranges between $20 and $55 per pond, or $17 and $46 per acre (see van Kooten et al. 2011). These values include the opportunity cost of retaining wetlands, which would be the equivalent of the net return to cropping as used in this model. Thus, for our base case scenario, we assume a lower level of $10/ac for the annual marginal (restoration) cost of retaining wetlands.

We estimate the duck production function using a logistic functional form:

$$g(D_t, W_t) = \eta D_t \left(1 - \frac{D_t}{\gamma W_t^b}\right), \quad (19)$$

where γW_t^b is the carrying capacity of the prairie pothole ecosystem and η is the intrinsic growth rate. We use data on breeding ducks and immature offspring, and on wetland habitat (May ponds measured in acres), for southern Alberta, Saskatchewan and Manitoba, thus encompassing strata 26 through 40 (Figure 1), for the period 1955 to 2008 (U.S. Fish and Wildlife Service 2010). Using nonlinear least squares regression, we estimate the following relation:

$$g(D_t, W_t) = 2.85\, D\left(1 - \frac{D}{14.25 W^{.0.91}}\right), \; R^2 = 0.56, \quad (20)$$

(10.08) (4.76) (4.61)

where t-statistics based on Newey-West HAC standard errors are provided in parentheses.

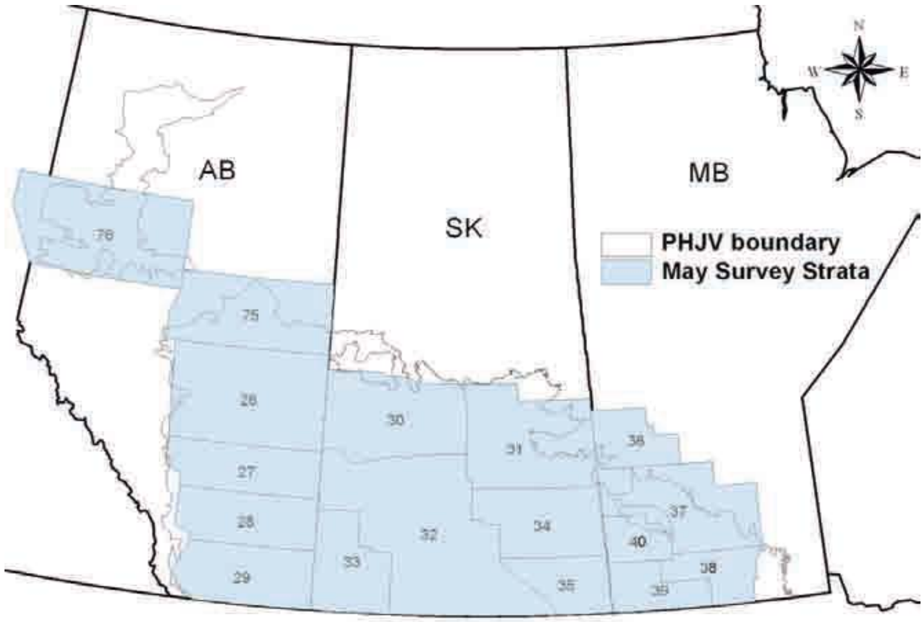

Figure 1: US Fish and Wildlife Service May Survey Strata (PHJV, 2009)

The wetlands state equation (4) is parameterized using nonlinear least squares regression. As noted, wetlands data are available from the U.S. Fish and Wildlife Service (2010). SPI data are from the North American Drought Monitor;[1] the SPI variable was constructed using averages from several weather stations in the study region. The SPI ranges from –4 to +4, with negative values indicating dry conditions and positive values wet ones. A value of –1 or less is an indicator of drought, with drought severity increasing as the SPI value falls. The nonlinear least squares regression for the wetlands equation is as follows:

$$W_{t+1} = \underset{(6.92)}{1.91} + \underset{(3.99)}{0.32} W_t \, e^{SPI_t}, \quad R^2 = 0.24, \qquad (21)$$

where t-statistics are again provided in parentheses. All estimated coefficients have the

[1] Retrieved online at http://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/

expected sign and are statistically significant at the 1% level.

Finally, we employ Hammack and Brown's (1974, p.50) values for intra-year duck survival rates for the period between breeding in May and the start of hunting season in September (s_1) and for the period after hunting season until breeding begins (s_2). We also adopt their value for the underreporting of bird kills by hunters (π), and van Kooten et al.'s (2011) amenity (viewing) value of $1 per duck.

A summary of the base-case functional forms and parameter values is provided in Table 1. Using these and solving equations (12) through (18), we find the base scenario, steady-state values of the variables $W, D, h, a, \lambda^D, \lambda^W$ *and* θ (Table 2).

Table 1: Model Functions and Parameters used in Simulations

Item	Base Case Value
Marginal hunter benefit function	$\partial v/\partial h = 46.8\, h^{-0.6}$
Marginal product of wetlands in duck production	$\partial g/\partial W = 0.18 D^2 W^{-1.91}$
Marginal product of breeding ducks	$\partial g/\partial D = 2.85 - 0.4 D W^{-0.91}$
Intra-year duck survival rates	$s_1 = 0.95$, $s_2 = 0.80$
Marginal cost of protecting wetlands	$c = C'(W) = \$\ 10$
Net revenue from cropping	$42
Marginal amenity value of wetlands	$B'(W) = \$45$
Marginal non-hunting value of a duck	$\alpha = \$1$
Adjustment for underreporting of kills	$\pi = 1.35$
Total land constraint, $\bar{A}$	83.57
Average SPI for period 1955-2008	–0.02

Table 2: Historic and Steady State Values of Wetlands, Duck Population, Duck Harvest and Cropped Area

	Wetlands ($\times10^6$ acres)	Ducks ($\times10^6$)	Duck harvests ($\times10^6$)	Cropped area ($\times10^6$ acres)	Shadow value of ducks (\$/duck)	Shadow value of wetlands (\$/ac)
Historic [a]	2.95	13.10	12.30	80.60	–	–
Base case[b]	2.79	16.78	15.24	80.76	9.03	68.04

[a] Source: Ponds and ducks are for Canada's prairie region and based on the average of 1955-2008 data from the U.S. Fish and Wildlife Service (http://mbdcapps.fws.gov/); harvest is the average of total 2007-2008 U.S. harvest (www.fws.gov/migratorybirds/NewReportsPublications/HIP/hip.htm).

[b] Based on bioeconomic model that takes into account amenity values of wetlands and ducks.

The results in Table 2 indicate that wetland retention will equal 2.79 million acres, which is lower than historic levels. In theory, the model will solve for the historic value of wetlands, but the value is slightly different due to white noise in estimating regression equation (4). Notice that when the model (approximately) calibrates to historic values of wetlands, the shadow value of wetlands is $68 per acre, which is higher than the return to cropping. This suggests that it is socially beneficial to have more lands in wetlands, indicating that the historic area in wetlands is lower than socially desirable. This result is similar to that of the earliest bioeconomic studies (Brown and Hammack 1973). We proceed with a value of 2.79 million acres as the base case for this study, and estimate the effect of climate change in comparison with this level.

Finally, if managed to maximize social welfare, ducks and harvests should have been significantly higher than historic levels. The reason that these values are so much higher than historic levels, whereas wetlands levels are lower than historic values, is the result of incorporating the amenity value of ducks and the value of duck harvests.

Results by Province and Stratum

By solving the model for each sub-region, we can provide policymakers with more information that might enable them to better focus wetlands conservation efforts. Further, we can get a better idea of where climate change effects on wetlands will be the most pronounced. To solve the regional models, however, it is necessary to make changes to the values in Table 1; it is necessary to re-parameterize equations (12) through (18) for each province and stratum separately, and then solve the model for each sub-region.

First, consider the logistic growth function and wetland state equations for each province and strata. Data are available on wetlands and waterfowl for each stratum from the U.S. Fish and Wildlife Service's (2010) Annual May Waterfowl Survey, while climate data are from weather stations in each of the 15 strata. The parameter values from the logistic equation and wetlands state equation are provided in Table 3.

Waterfowl population data at the disaggregated (strata) level are much more varied than aggregate data, which produced unrealistic parameter estimates for the logistic equation (19) in several strata. Upon excluding outliers for wetlands and waterfowl, we obtained a better statistical fit; in Table 3, therefore, we include the number of observations used to estimate the logistic function, with 54 observations (1955-2008) available. For some strata with very volatile data (strata 29, 30 and 36), a significant number of observations were eliminated. The wetlands function (4) was estimated using all available observations from 1955-2008.

Second, the hunter valuation function in Table 1 is calibrated on the basis of PPR-wide harvest levels. Following the approach employed by van Kooten et al. (2011), we re-specify the valuation function as $v(h)= 61h^{0.409}$ for provincial analysis and

$v(h)=27h^{0.409}$ for each stratum. However, this assumes that valuation of ducks is equal across all regions, which is a heroic assumption necessitated by lack of valuation information.

Table 3: Sub-Region Parameter Estimates for the Logistic and Wetland State Equations by Strata and Province

		Logistic function			Wetlands State	
Strata	*Obs.*	η	γ	b	β_0	β_1
26	47	2.08	11.58	0.61	0.26	0.27
27	46	2.64	11.30	0.74	0.08	0.20
28	48	2.65	8.70	0.42	0.07	0.14
29	39	2.64	4.75	0.50	0.07	0.16
30	24	3.13	21.90	1.14	0.17	0.25
31	43	2.18	38.80	1.48	0.27	0.25
32	44	2.80	23.90	0.94	0.31	0.24
33	54	2.84	15.50	0.86	0.08	0.11
34	54	3.04	8.42	0.71	0.25	0.29
35	54	2.30	29.60	0.70	0.14	0.31
36	35	2.25	8.87	0.98	0.04	0.19
37	54	2.50	16.50	0.94	0.19	0.14
38	47	2.45	1.78	0.63	0.03	0.20
39	44	2.50	17.70	1.05	0.08	0.32
40	54	2.87	3.97	0.41	0.10	0.16
Province						
Manitoba	51	3.02	7.19	0.64	0.43	0.24
Saskatchewan	47	2.80	14.90	1.11	1.17	0.28
Alberta	46	3.12	13.28	0.67	0.46	0.27

η, γ and b are the parameters in the logistic equation (20).
β_0 and β_1 refer, respectively, to the intercept and slope parameters in equation (4).

Finally, we adjust the net revenue from cropping by province and stratum. While information is available from Statistics Canada to facilitate this for provinces, we lack stratum-level data on revenue. As a result, we adjust the net revenue in Table 1 using crop yields for wheat, barley and oats. These are the most prominent crops for which there is data for all areas of the study region. We multiply the net revenue by the crop yield in a given stratum divided by average crop yield for the entire PPR.

The steady-state values for wetlands area, duck population, duck harvests and cropland by province and strata are provided in Tables 4 and 5, respectively. Historic data on duck harvests are not available at the sub-region (province or stratum) level, so only the aggregate levels for the PPR from Table 2 are reported.

Table 4: Historic and Base Case Steady State Values of Wetlands Area, Duck Population, Duck Harvests and Cropped Area, by Province (millions)

	Province			
Item	Alberta	Saskatchewan	Manitoba	TOTAL
Historic Values				
Wetlands (acres)	0.64	1.72	0.59	2.95
Duck populations	4.30	7.50	1.30	13.1
Duck harvests	—	—	—	12.30
Cropped area (acres)	21.4	48.10	11.1	80.60
Base Case Optimal Values				
Wetlands (acres)	0.62	1.62	0.56	2.8
Duck populations	4.48	12.1	2.26	18.84
Duck harvests	4.48	10.43	2.24	17.15
Cropped area (acres)	21.42	48.2	11.13	80.75
Wetland shadow value ($/ac)	96.4	62.43	60.98	68.04

Results from Tables 4 and 5 confirm the overall conclusion from Table 2. Wetlands retention is lower than historic averages, due to estimation of the wetlands state equation. However, the average shadow value of wetlands is higher than the return to cropping. Thus, it is socially optimal to increase wetlands above historic levels in the steady state. Further, steady state levels of ducks and harvests are found to be higher than historic values, due to the value of ducks and harvests. The results of Tables 4 and 5 provide a base case from which to estimate climate change effects, which may be very different by sub-region.

Table 5: Historic (H) and Optimal Steady-State (SS) Values of Wetlands (acres), Duck Population, Duck Harvests and Cropped Area (acres) by Stratum and Total (millions)

Stratum	26		27		28		29	
	H	***SS***	***H***	***SS***	***H***	***SS***	***H***	***SS***
Wetland	0.37	0.36	0.11	0.1	0.08	0.08	0.08	0.08
Ducks	2.45	2.94	0.71	0.96	0.63	1.35	0.5	0.59
Harvest		2.83		0.81		1.13		0.5
Crops	9.47	9.48	5.1	5.11	2.12	2.12	4.73	4.73
Stratum	30		31		32		33	
	H	***SS***	***H***	***SS***	***H***	***SS***	***H***	***SS***
Wetland	0.24	0.22	0.38	0.36	0.42	0.4	0.09	0.08
Ducks	1.34	1.84	1.42	1.42	2.57	2.57	0.43	0.084
Harvest		1.84		1.42		2.57		0.77
Crops	8.45	8.47	7.86	7.88	18.22	18.24	3.41	3.42
Stratum	34		35		36		37	
	H	***SS***	***H***	***SS***	***H***	***SS***	***H***	***SS***
Wetland	0.37	0.35	0.22	0.2	0.06	0.05	0.24	0.23
Ducks	1.04	1.86	0.69	0.69	0.06	0.22	0.55	1.86
Harvest		1.8		0.69		0.16		1.43
Crops	6.58	6.6	3.53	3.55	0.58	0.59	3.1	3.11
Stratum	38		39		40		**Total Region**	
	H	***SS***	***H***	***SS***	***H***	***SS***	***H***	***SS***
Wetland	0.04	0.04	0.13	0.11	0.13	0.12	2.95	2.78
Ducks	0.07	0.1	0.2	0.82	0.44	0.77	13.1	18.83
Harvest		0.08		0.65		0.71	12.3	17.41
Crops	3.02	3.02	2.93	2.95	1.49	1.5	80.6	80.77

For strata 31, 32 and 35, the logistic model does not fit the data well, and historic values were assumed for ducks in these strata.

Clearly, there are differences in results as one changes the level of aggregation. In particular, the socially optimal duck populations and duck harvests are higher in the disaggregated analysis, but this might be due to the particularly large estimated parameters on the carrying capacity for strata 31-37 (see Table 3). Nonetheless, the major results remain consistent across the three levels of analysis and the model provides a base case from which climate change effects can be estimated.

5. EFFECT OF CLIMATE CHANGE ON WETLANDS RETENTION

To estimate the impact of climate on the baseline values given in Tables 2, 4 and 5, we specify several climate change scenarios. We first present climate change scenarios that pertain to the entire PPR, and then discuss necessary adjustments to the scenarios for regional analysis, followed by our estimates of the effects of these policies.

Policy Scenarios

Based on IPCC (2007), climate predictions indicate that there will be warming in the PPR, although there is uncertainty as to whether the climate will become more or less dry. Given this uncertainty, it is important to estimate the effects of both a wetter and drier climate on wetlands and waterfowl management in the PPR. Thus, we adopt the following climate change scenarios from Johnson et al. (2005):

1. an increase in temperature of 3^oC, no change in precipitation;
2. an increase in temperature of 3^oC, a decrease in precipitation of 20%; and
3. an increase in temperature of 3^oC, an increase in precipitation of 20%.

We estimate the impact of temperature and precipitation on SPI in the study region using linear regression, and use the regression results to find the SPI values that correspond to the above scenarios. We then change the SPI variable and re-solve the optimal control model to determine the effect of climate change on waterfowl and wetlands management, assuming all else remains the same. The effects of temperature and precipitation on SPI are calculated using the following OLS regression result:

$$SPI= -0.03 + 0.0018\times Precipitation - 0.0695\times Temperature,\ R^2= 0.60 \qquad (22)$$
$$(-0.14) \quad (5.68) \qquad\qquad (-4.63)$$

SPI is the standardized precipitation index, precipitation is annual and temperature is the mean annual maximum temperature. Temperature and precipitation data are available from Environment Canada's Historical Weather and Climate Data.[2] At mean values of precipitation and temperature, the model predicts SPI = –0.02, which is the actual mean value for the PPR. For climate scenarios 1, 2 and 3, the corresponding SPI values predicted by the regression equation are –0.22, –0.36 and –0.08.

Climate change will also indirectly impact wetlands due to policies that mitigate climate change, such as those that subsidize production of biofuel crops. In 2008, the Government of Canada introduced a Renewable Fuel Standard (RFS) that requires 5% renewable content in gasoline by 2010 and 2% renewable content in diesel and home heating oil by 2012.[3] This standard will increase demand for grains that are used to make biodiesel, and will increase production of canola in the prairie pothole region.

Mussell (2010) estimates that this policy will increase the price of canola by $19 per tonne for the 2-percent blend, and $200 for the 5-percent blend. Given current prices, the increase due to the RFS policy represents a 7% increase in the price of canola for the 2-percent blend and 75% increase for the 5-percent blend. Since the latter result seems quite high, we consider the impact of increasing the price of canola by 15%. We estimate the impact of canola price on total cropped land using OLS and data from 1985-2010:

[2] Retrieved online at http://www.climate.weatheroffice.gc.ca/Welcome_e.html
[3] Information from: www.topcropmanager.com/content/view/4348/38/ (accessed December 22, 2010).

$$a_t = 63.3 + 0.025 \times P_c, \qquad R^2 = 0.57, \qquad (23)$$
$$(26.04) \quad (3.38)$$

where a_t is the amount of cropped land described above (in millions of acres), P_c is the price of canola (in $ per tonne, obtained from Statistics Canada) and t-values are presented in parenthesis.

Based on this regression, a 15% increase in the price of canola will increase cultivated land by 1.25 million acres, and we assume this increase comes at the expense of wetlands. This represents a very small percentage increase in crops, since increases in canola will also come by converting pasture or summer fallow lands (which are incorporated in a_t) or unimproved land outside the extensive margin. Further, since canola can be planted in some regions in rotation with winter wheat, and winter wheat is suitable waterfowl habitat, the impact of this increased canola on waterfowl production (via reduced wetlands) may not be lessened. Yet, it is not an unreasonable to assume that 1.25 million acres will come from wetlands; at worst, it could be interpreted as an upper bound of climate change effects on wetlands as a consequence of biofuel policies. In contrast, the direct climate effect considered in isolation (i.e., just the temperature increase and change in precipitation without added conversion of wetlands from biofuel policies) can be thought of as a lower bound.

In addition to the historic levels of wetlands, duck population, duck harvests and cropped acres, the model solves a baseline scenario that provides optimal values for these variables if externality effects are taken into account (tables 2, 4 and 5). Then we consider the climate scenarios (1, 2 and 3) discussed above and, for each, consider a further impact from diverting 1.25 million acres of wetlands to the production of canola for biodiesel. We refer to these scenarios as 1F, 2F and 3F, and they represent the total (temperature and precipitation change plus biofuel standard) impact of climate change on optimal wetlands and waterfowl. The same scenarios are investigated for each of the sub-regions, whether provinces or strata. We estimate the change in SPI for each sub-region using equation (22). To allocate the extra 1.25 million of cropped land among the provinces or strata, we simply increase cropped area in each sub region by the weight of historically cropped land in the stratum or province to total cropped land in the PPR.

Results of Climate Change on Wetlands

A summary of the results of climate change impacts on optimal wetlands retention and waterfowl management is provided in Table 6. The summary provides results for the entire pothole region, as well as the aggregated results for the sub-region models when aggregation is done by province and by strata. [4]The base values from the original model (Tables 2, 4 and 5) are provided in Table 6, as are estimates of the impact of climate change on optimal management corresponding to policy scenarios 1, 1F, 2, 2F, 3 and 3F.

In the aggregate analysis, optimal wetlands retention given no land use change and only change in temperature (scenario 1) is 2.58 million acres. This represents a reduction from baseline optimal values of 8%. The optimal duck population is 15.57 million in this scenario, a reduction of about 7% from the baseline value.

[4] Results by individual provinces or by stratum are available upon request from the authors.

Table 6: The Effect of Climate Change on Optimal Levels of Wetlands, Duck Population, Duck Harvest and Cropped Area for Different Levels of Regional Analysis

Item	Wetlands ($\times 10^6$ acres)	Duck population ($\times 10^6$)	Duck harvests ($\times 10^6$)	Cropped area ($\times 10^6$ acres)
Historic[a]	2.95	13.1	12.3	80.6
Base-case[b]				
Entire pothole region	2.79	16.78	15.24	80.76
Province level	2.8	18.84	17.15	80.75
Stratum level	2.78	18.83	17.41	80.77
1. 3°C temperature increase; no change in precipitation				
Entire pothole region	2.58	15.57	14.16	80.97
Province level	2.68	18.01	16.43	80.87
Stratum level	2.69	18.33	16.5	80.86
1F. 3°C temperature increase; no change in precipitation & biofuel standard				
Entire pothole region	1.33	8.38	7.76	82.22
Province level	1.43	9.52	8.95	82.12
Stratum level	1.45	10.43	9.64	82.10
2. 3°C temperature increase; 20% decrease in precipitation				
Entire pothole region	2.47	14.99	13.65	81.08
Province level	2.51	16.81	15.42	81.04
Stratum level	2.54	17.45	16.14	81.01
2F. 3°C temperature increase;20% decrease in precipitation & biofuel standard				
Entire pothole region	1.23	7.78	7.22	82.32
Province level	1.26	8.43	7.99	82.29
Stratum level	1.10	9.6	8.87	82.45
3. 3°C temperature increase; 20% increase in precipitation				
Entire pothole region	2.73	16.37	14.87	80.82
Province level	2.92	19.65	17.79	80.63
Stratum level	2.89	18.77	17.36	80.66
3F. 3°C temperature increase; 20% increase in precipitation & biofuel standard				
Entire pothole region	1.47	9.20	8.52	82.08
Province level	1.67	11.1	10.34	81.88
Stratum level	1.64	11.56	10.73	81.91

[a] Ponds and ducks are for Canada's prairie region, based on U.S. Fish and Wildlife Service (http://mbdcapps.fws.gov/) average of 1955-2008 data; average 2007-2008 U.S. harvest (www.fws.gov/migratorybirds/NewReportsPublications/HIP/hip.htm).
[b] Based on solution to bioeconomic model accounting for the amenity values of wetlands and ducks.

The optimal level of aggregate wetlands to retain when we assume that, in addition to an increase in temperature of 3°C, precipitation declines by 20% (scenario 2) is 2.47 million acres, a reduction of 12% from the baseline. While these impacts are smaller than those found by Withey and van Kooten (2011) for the same scenario, the difference can be attributed to modeling differences. In particular, the wetlands state equation in this study captures the relation between wetlands and climate using a non-linear relationship, which produces different results. Under the assumption of increased precipitation (scenario 3), the effect of climate change on wetlands is negligible, with a reduction from the baseline case of only 2%. Thus, the effects of climate change alone on wetlands may range from almost negligible to as much as a 12% reduction.

When we include the effect of policies to mitigate climate change (scenarios 1F, 2F and 3F), we find that the optimal level of aggregate wetlands to retain falls even further – to 1.33 million acres under scenario 1F (temperature only), 1.23 million ac under 2F (decrease in precipitation) and 1.47 million ac under 3F (increase in precipitation). Thus, the total effect of climate change on optimal wetlands retention is a reduction of 53%, 56% and 47% for Scenarios 1F, 2F and 3F, respectively. In each case, the reduction in ducks and duck harvests is roughly proportionate to the reductions in wetlands. All three of these effects are larger than the climate change impact found by Withey and van Kooten (2011) as they did not consider the impacts of a biofuel policy. Indeed, it turns out that the climate mitigation policy has a larger impact on the loss of wetland habitat than does the predicted climate change. Therefore, studies that ignore the effect of government actions to avoid climate change may grossly underestimate the effect of climate change on future values of wetlands and waterfowl.

By analyzing the provincial and strata level results in Table 6, we gain additional insights. In particular, we can determine where wetlands may be most threatened in a changing climate. The remainder of this section focuses on scenarios 2 and 2F, where warming occurs but precipitation declines. These scenarios are chosen because disaggregated results for scenarios 1 and 1F are very similar, while there is only a minor change in optimal wetlands retention in any of the disaggregated regions for scenarios 3 and 3F.

Based on the provincial-level analysis in Table 6, the decrease in wetlands retention is 10.6% due to increased temperature and decreased precipitation (scenario 2), while the overall reduction in wetlands due to climate change is 55% (scenario 2F). These results are similar to the effects based on the aggregate analysis. Climate change impacts on wetlands in the PPR are driven primarily by reductions in wetlands in Saskatchewan, which is due primarily to land use change and not climate factors per se. The proportional loss in optimal wetlands area is highest for Alberta, and smallest for Manitoba, both in percentage terms and actual area. In terms of both direct climate effects and land use change effects, the overall impact on wetlands retention is highest in Saskatchewan, the percentage decrease is highest in Alberta and the effect is smallest in Manitoba.

The results in Table 6 based on strata level analysis indicate that climate factors will reduce optimal wetlands retention by 8.6% under climate scenario 2, while wetlands loss increases to 60% once the impact of biofuel policies is added to that of climate change (scenario 2F). The reduction in optimal wetlands to retain is the highest in strata 30-34 in Saskatchewan, and stratum 26 in Alberta. Further, wetlands loss is the highest (in percentage terms) in Alberta and it is optimal to drain all wetlands in strata 27 and 29 located southeastern Alberta, which is drier than the rest of the prairie pothole region. In the face of a drier climate, wetlands reductions will be the smallest in eastern parts of Saskatchewan (strata 35) and Manitoba. While the overall level of wetlands retention should still be highest in Saskatchewan under this ‘dry’ scenario, the post climate change in wetlands in Manitoba should be greater than Alberta.

Overall, if precipitation increases as a result of predicted climate change during the 21st century, there will be very little climate induced change in optimal wetlands retention relative to recent history. Nonetheless, biofuel policies meant to mitigate climate change will lead to wetland losses, primarily in Saskatchewan and Alberta. Further, Manitoba will be the least affected by a warmer, drier climate, and will be the best source of wetlands habitat if a drier climate prevails in the future. Thus, wetlands retention policies should focus on Saskatchewan and Manitoba, particularly if a drier climate is expected, with the most productive waterfowl habitat located in northeastern strata in such a case. This result is consistent with the findings of Johnson et al. (2005), who indicate that a dry climate will push available wetlands habitat to the northern and eastern parts of Canada’s grain belt.

6. CONCLUSIONS

This paper specifies a discrete bioeconomic model of waterfowl management and agricultural cropping to determine the impact of climate change on wetlands and waterfowl in Canada’s PPR. Previous studies that estimated the impact of potential future climate change on wetlands in the PPR focused solely on direct climate effects, ignoring important effects of climate change that are caused by adopting mitigation policies, such as subsidies to promote biofuel production. By including cropping decisions in the model and wetlands as a state variable, we explicitly model the total effect of climate change.

To optimize social wellbeing, the model indicates that levels of wetlands and waterfowl should be higher than historical levels. As expected, climate change is likely to reduce the socially desirable level of wetlands to retain by as much as 47 to 56 percent from baseline values, depending on climate conditions that are expected to prevail. However, more than three quarters of this reduction in wetlands is driven by land use change due to biofuel policies. To the extent that our disaggregation is appropriate, the results confirm those of others (e.g., Johnson et al. 2005): If future climate change leads to increased drought in the region, the focus of efforts to protect wetlands should be on the northeastern and eastern parts of the prairie pothole region.

Overall, the effect of climate change on waterfowl habitat could be severe, and agricultural policies could play a vital role in the demise of wetlands. While Withey and van Kooten (2011) consider some policy implications of this line of research, the results of the waterfowl management model presented in this paper provide two additional insights. First, we find that climate change adaption strategies that promote biofuel production can significantly decrease the level of wetlands retention. That in turn will reduce the greenhouse gas stored in wetlands, offsetting the CO_2 emission reductions due to the original biofuel policy. Thus, it is crucial that polices promoting climate change adaptation via biofuel production also consider the costs due to potential loss of wetlands, and be weighted against mitigation in wetlands. Second, the current results provide policy direction regarding where efforts should be concentrated in order to retain wetlands in the face of climate change.

One aspect of this study that is missing is explicit spatial analysis. By solving for optimal wetland retention by region, we take a first step towards understanding how climate change will impact wetlands retention, and also where wetlands and waterfowl should be conserved. However, one limitation of the current framework is that we assume that the different strata are independent. The next step is to build a model that allows for dependencies between the regions in order to determine the spatial impact of climate change. That is, in addition to the direct effect of climate change on wetlands retention in one area of the PPR, is there an indirect effect in adjoining areas? Future analyses need to consider how accounting for spatial and dynamic factors affects policy recommendations arising from the interplay between climate change, cropping incentives and protection of waterfowl habitat.

Acknowledgements: The authors wish to thank Agriculture and Agri-Food Canada's LEARN Network for research support, and Don Fullerton for helpful comments on an earlier draft of the manuscript.

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