Journal of Agricultural and Resource Economics 39(1):1–18 ISSN 1068-5502

Wetlands Retention and Optimal Management of Waterfowl Habitat under Climate Change

Patrick Withey and G. Cornelis van Kooten

We develop a positive mathematical programming model to investigate the impact of climate change on land use in the prairie pothole region of western Canada, with particular focus on wetlands retention. We examine the effect of climate change and biofuel policies that are implemented to mitigate climate change on wetlands retention. Simulation results indicate that a drier climate could decrease wetlands by as much as 38% if the externality benefits of wetlands are considered, but by nearly 80% if they are not. Reductions in wetlands are most pronounced in the south-central areas of the region.

Key words: biofuels, climate change, land-use change, positive mathematical programming, prairie pothole region, wetlands conservation

Introduction

Wetlands are among the world's most important ecosystems, sometimes referred to as the "kidneys of the landscape" or an "ecological supermarket" (Mitsch and Gosselink, 2007, p. 4). Because of their ability to filter water, support a rich biodiversity, and store greenhouse gases (especially methane and carbon dioxide), wetlands provide significant economic value to society. Nonetheless, wetlands in western Canada, for example, have been and continue to be drained as a result of agricultural development. The social benefits of wetlands do not typically accrue to landowners, so they continue to convert them to agricultural production.

Wetlands in western Canada's grain belt are also threatened by climate change. A potentially drier climate is forecast to significantly reduce the wetlands to be retained over the next 100 years (Johnson et al., 2005, 2010). Climate assessments predict that air temperatures in the region could rise by 3.2°F (1.8°C) to 7.2°F (4.0°C) by 2100, while estimates of changes in average annual precipitation during the next 100 years vary between a decrease of 5% and an increase of 10% (Intergovernmental Panel on Climate Change, 2007). Some regional assessments anticipate precipitation increases of as much as 20%, but with significant decline in summer months (Ojima and Lackett, 2002). To take into account potential extremes in precipitation, some studies have examined the extreme impact of climate change on wetlands by assuming a decline in precipitation of 20% in one scenario and an increase of 20% in another (Johnson et al., 2005; Withey and van Kooten, 2011, 2013). Often forgotten, however, is the fact that wetlands are also threatened by climate mitigation policies, especially policies that subsidize the production of energy crops (Searchinger et al., 2008). Both climate change and policies to mitigate it could adversely affect the future of wetlands in western Canada.

Given the significant benefits that wetlands provide in producing migratory waterfowl (which have hunting and viewing value) and their ecosystem amenity values (van Kooten, Whitey, and Wong, 2011), it is essential that wetlands in western Canada be managed to optimize social

---

Patrick Withey is in the Department of Economics at St. Francis Xavier University. G. Cornelis van Kooten is in the Department of Economics at the University of Victoria.

The authors wish to thank Agriculture and Agri-Food Canada's ERCA Network for research support.

Review coordinated by Gregmar I. Galinato.

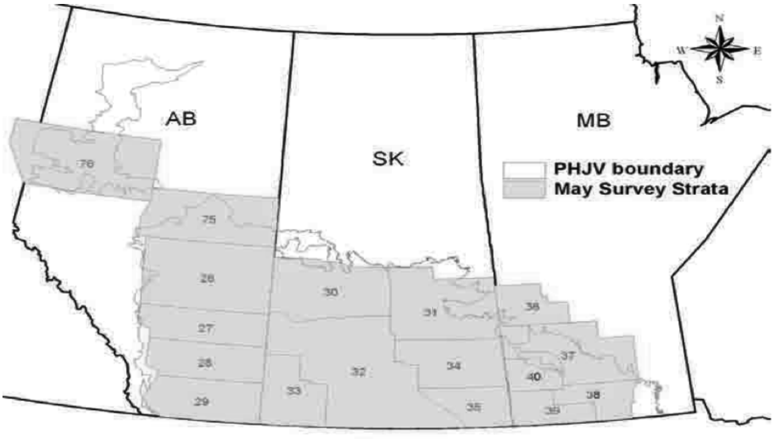

Figure 1. U.S. Fish and Wildlife Service May Survey Strata

Source: Prairie Habitat Joint Venture (2008).

welfare over time; it is also important to understand how climate change might impact wetlands management. This study provides an empirical analysis predicting land-use change due to climate change. The specific objectives of the current research are to (1) investigate the effect that projected future aridity will have on wetlands in the study region (figure 1), the prairie pothole region (PPR); (2) examine the impact that climate mitigation policies will have on wetlands; (3) consider the divergence in optimal land use between private landowners and social planners; and (4) determine how a drier climate will affect wetlands across the heterogeneous regions of the PPR.

Howitt's (1995) positive mathematical programming (PMP) approach is used to calibrate a land-use model for the PPR study region. The approach is termed positive because it requires calibration to observed data. PMP requires three stages. The first stage requires the solution to a linear program that includes calibration constraints over and above the usual resource and non-negativity constraints. Rather than just adding arbitrary calibration constraints to the linear program to replicate observed land use, the second stage of the PMP method uses the shadow prices associated with such constraints to specify an appropriate nonlinear yield function. This function takes into account the reasons why farmers plant a given crop. In the third stage, the nonlinear optimization problem is solved, and the model calibrates to observed acreage. In this last stage, parameter values can be adjusted to estimate the impact of policy or a change in conditions. PMP is used by Agriculture and Agri-Food Canada to calibrate the Canadian Regional Agriculture Model (CRAM), which includes environmental components to estimate the effect of different policies on land use.[1] PMP is also employed in the United States and Europe to examine the impact of various agricultural and environmental policies on rural land use (see de Frahan et al., 2007; Heckelei, Britz, and Zhang, 2012, for excellent reviews). However, to our knowledge, no studies use PMP to model land-use change in the context of wetlands management and climate change.

Studies of wetlands management have generally employed an optimal control framework. In this regard, Brown and his colleagues (Brown and Hammack, 1973; Hammack and Brown, 1974; Brown, Hammack, and Tillman, 1976) were the first to use mathematical bioeconomic models to address wetlands conservation. They specified a discrete optimal control model that maximizes benefits to hunters minus the costs of providing wetlands subject to the waterfowl population dynamics. Johnson et al. (1997) extended their model to account for uncertainly, while van Kooten, Whitey, and Wong (2011) included the ecosystem amenity value of wetlands and the viewing value of waterfowl.

---

[1] Model details can be found at http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5351.ph (accessed September 10, 2012).

Each of these studies reached a similar conclusion: wetlands are and have historically been below socially optimal levels.

Several studies have looked at the impact of climate change on wetlands. Larson (1995) and Sorenson et al. (1998) employed regression analyses to estimate the impact of climate change on wetlands in parts of the PPR. Johnson et al. (2005) used a simulation model to estimate the spatial impact of climate change on wetlands, concluding that given global warming the most productive waterfowl habitat will be confined to the northern and eastern parts of the PPR. None of these studies included economic considerations. An exception is two studies by Withey and van Kooten (2011, 2013), who extended van Kooten, Withey, and Wong's (2011) bioeconomic (optimal control) model to consider the impact of climate change on wetlands management.

Using an estimated waterfowl population growth equation that explicitly includes wetlands as a factor-impacting carrying capacity, Withey and van Kooten (2011) found optimal steady-state levels of duck populations, harvests, and wetlands retention under various climate change scenarios. Climate change could decrease optimal wetlands retention by as much as 38% and optimal duck populations and associated harvests by more than 65%. Withey and van Kooten (2013) extended the optimal control model to include cropping as a control variable in addition to waterfowl harvests. They then compared optimal duck harvest levels and wetlands retention under different climate scenarios and, importantly, under government policies that encourage energy crop production to mitigate climate change. The authors found that policies promoting production of energy crops have a larger negative impact on wetlands retention and waterfowl populations than potential climate change. In the worst case, wetlands area could decline by 56%, but more than 60% of this projected decline (35% of the 56%) would be attributable to the biofuels policy.

In the current application, we employ a multiregional land-use model that allows us explicitly to model the tradeoffs between agricultural production and wetlands management. We use the PMP method to calibrate separate models for each of strata 26 through 40 used by the U.S. Fish and Wildlife Service's Population Survey (figure 1). In doing so, we employ Canada's 2006 Census as our base year and calibrate the model for nine land uses: spring wheat, winter wheat, barley, oats, dry field peas, canola, tame pasture, hay land, and wetlands.[2] Lacking data on net returns to wetlands, the model sums private (wetlands represent a cost) and public (positive social benefits) returns. In addition to base-case results, we estimate how a warmer, drier future climate will induce changes in crop yields and impact land use. A panel-regression model is specified to estimate the impact of climate variables on crop yields and wetlands area; the estimated change in yields based on the econometric model is incorporated into the third stage of the PMP model to predict changes in land use due to climate change. We focus on the case of a warmer climate with decreased precipitation but discuss the effects of alternative scenarios in the results section. Similar to Withey and van Kooten (2013), we also estimate the impact of a policy-induced increase in the demand for biofuels; this is done by examining the impacts on land use of higher net returns to canola (rapeseed) production, the principal energy crop in our study region.

As an indicator of the potential severity of climate change, our results predict that, in a drier climate, the wetlands area to be retained in the study region could potentially be reduced by as much as 38% from 2006, even if the social benefits of wetlands are considered. If the social benefits of wetlands are ignored, the decrease in wetlands could be significantly higher. Contrary to Withey and van Kooten (2013), however, direct climate effects will have a greater impact than incentives to increase biofuel production. Not surprisingly, results are heterogeneous across regions within the prairie pothole region, with differences in some instances quite pronounced.

---

[2] These nine land uses represent 84% of total land use in the study region.

Model Specification

Positive mathematical programming relies on the notion that any (linear) calibration constraint can be represented in the objective function as a nonlinear cost or yield function (Howitt, 1995). Rather than adding arbitrary calibration constraints to a linear program (LP) to replicate observed land use, the PMP method uses the shadow prices associated with such constraints to specify an appropriate nonlinear yield function. The calibrated model is then solved to replicate the observed values exactly. The nonlinear yield function derived using PMP takes into account farmers' reasons for planting multiple crops, such as risk or unobserved costs. It also also captures land-quality heterogeneity and the fact that land suitability varies spatially for a given crop (see Heckelei, Britz, and Zhang, 2012). Calibrated parameters represent those that best describe how the farmer chose the observed allocation of land uses.

In the first stage of the PMP approach, an LP is solved that maximizes net returns to land uses, subject to resource and calibration constraints:

$$\max_{x_k} \sum_{k=1}^{n} (p_k x_k y_k - c_k x_k); \tag{1}$$

$$\text{s.t.} \sum_{k=1}^{n} a_{jk} x_k \leq \bar{R}_j, \ \forall\ j \text{ (Resource constraint; } \lambda_{1,j}); \tag{2}$$

$$x_k \leq x_k^{obs} + \varepsilon_k, \ \forall\ k \text{ (Calibration contraint; } \lambda_{2,k}); \tag{3}$$

$$x_k \geq 0, \ \forall\ k \text{ (Non-negativity constraint)}; \tag{4}$$

where p_k, y_k, and c_k are the prices ($/bu), yields (bu/ac), and average costs ($/ac) for each of land uses k (of which there are n); the allocation of land to activity k is denoted x_k; a_{jk} are the technical coefficients of production (the amount of resource j required per unit of x_k); $\bar{R}_j$ is the total amount of resource j that is available; and $\lambda_{1,j}$ and $\lambda_{2,k}$ are the dual values associated with constraints (2) and (3), respectively. As with the CRAM model, we consider only the land resource so that $a_{l \text{ and } j} = 1, \ \forall\ j$, and we only have one constraint equation in constraint (2), so that there is only one shadow price, λ_1. The calibration constraints (3) are needed to implement PMP, where x_k^{obs} are the observed areas in each land use and ε_k are perturbation terms that are chosen to be very small positive numbers. The model is solved for each of the fifteen strata for nine available land-use activities.

Dual values from the LP described by equations (1) through (4) are then used to estimate the parameters of the yield function for each crop in each region. Assume a quadratic yield function, $y_k = (\beta_k - \gamma_k x_k)$.[3] The solution to the LP given by equations (1) through (4) yields the shadow prices, λ_{2k}, associated with the calibration constraints (3). These are equal to the difference between the value of the average product (VAP) and the value of the marginal product (VMP) of land (Howitt, 1995), or $\lambda_{2k} = VAP_k - VMP_k$. For each crop k, we multiply its yield y_k by the associated output price p_k and acres planted x_k to obtain the total value of land. We then find VAP_k by dividing by x_k, and VMP_k by taking first derivatives, so that

$$VAP_k = p_k(\beta_k - \gamma_k x_k) \text{ and } VMP_k = p_k(\beta_k - 2\gamma_k x_k). \tag{5}$$

Given the dual values for each calibrated land use k (denoted λ_{2k}), as well as data on p_k, y_k, and x_k^{obs}, it is possible to calibrate quadratic yield functions that represent the decisions of landowners in

---

[3] A quadratic function is used most often because of its simplicity and because the solution to the resulting constrained optimization problem results in first-order derivatives that are linear. de Frahan et al. (2007) use a quadratic function in an analysis of Belgian agriculture, while Heckelei, Britz, and Zhang (2012, p. 115) point out in their excellent review of PMP that a quadratic functional form is most widely used in the empirical applications. Likewise, Paris (2011, p. 347) also appears to favor the quadratic functional form, probably for its ease of use.

a given region as follows:

$$\gamma_k = \frac{\lambda_{2k}}{p_k \times x_k^{obs}} \tag{6}$$

and

$$\beta_k = y_k + (\gamma_k \times x_k^{obs}). \tag{7}$$

The revised value function is then given by: $p_k(\beta_k - \gamma_k x_k)x_k - c_k x_k$, with $(\beta_k - \gamma_k x_k)$ replacing y_k.

The perturbation coefficient ε_i in equation (3) decouples the shadow prices for equations (2) and (3) and enables the dual values from equation (3) to be used to calculate the production function parameters. However, since the number of constraints exceeds the number of activities, one of the calibration dual values will be zero. This least profitable activity is considered a marginal crop, for which the calibration constraint does not bind and the activity is constrained only by the land-use equation (2).

When λ_{2k} is equal to zero, one cannot tell the difference between the average and marginal product of land, and the yield is assumed to be constant, since $\gamma_i = 0$. Therefore, additional empirical information is required to calibrate a decreasing yield function for marginal activities. Following Howitt (1995), one can use expected yield variation of the marginal crops as additional information; for simplicity, we assume that expected yield variation in all regions and for all crops is 20% from the mean. While this assumption is overly simplistic, it has little effect on the results since there are few marginal activities in the base case. This assumed yield reduction causes a 20% reduction in the opportunity cost of land (λ_1) in producing the marginal crop. For the first-order conditions to hold, a decrease in λ_1 will be offset by an increase in the value of λ_2 for the marginal crop, which is denoted $\bar{\lambda}_{2m}$ and can be used to calculate the nonlinear yield function for the marginal activity. All other λ_{2k} values must then be adjusted by$\bar{\lambda}_{2m}$.[4]

The final constrained optimization problem to solve now becomes:

$$\max_{x_k} \sum_{k=1}^{n} [p_k(\beta_k - \gamma_k x_k)x_k - c_k x_k]; \tag{8}$$

$$\text{s.t.} \sum_{k=1}^{n} a_{jk} x_k \leq \bar{R}_j,\ \forall\ j \text{ (Resource constraint; } \lambda 1,\ j); \tag{9}$$

$$x_k \geq 0,\ \forall\ k \text{ (Non-negativity constraint);} \tag{10}$$

This model uses the calibrated yield function from the second stage to represent landowners' decisions. Using only the resource constraint (9) and non-negativity constraints (10), the solution replicates the observed allocation for a base year. For different scenarios (discussed below), only the parameters in equation (8) need to be adjusted.

Data

We require observed area (x), yield (y), price (p), and variable cost (c) data for each land use in each stratum in figure 1 to solve the land-use model. We want to calibrate our model to the most recent year for which data are available because of ongoing changes in agricultural policies and climate change. Since our data on land use come from the latest Census of Agriculture (Statistics Canada, 2007), the most recent year for calibration purposes is 2006. Table 1 provides the number of acres seeded by major crops in the Prairie Provinces in 2006 as well as historic averages.[5] Spring wheat acreage has declined since the 1950s, while area in canola has increased. Nonetheless, the pattern of land use in 2006 is representative of land uses over the past decade.

---

[4] See Howitt (1995, p. 337) for more details and an example.

[5] Data are from Statistics Canada's Cansim Table 001-0017.

Table 1. Agricultural Land Use in the Canadian Prairie Provinces (1,000s of acres)

	Spring Wheat	Winter Wheat	Oats	Barley	Peas	Canola
2006	18,324	745	4,532	8,455	3,109	12,957
1950–2010	22,413	539	4,914	9,532	919	6,073
2000–2010	17,391	759	4,112	9,727	3,339	13,330

Crops

The land-use data from each of the Census Consolidated Subdivisions (CCS) in the Census of Agriculture (Statistics Canada, 2007) are overlapped with stratum-level waterfowl population and wetland data from the U.S. Fish and Wildlife Service (2010). In a few cases when part of a CCS was in two different strata, the data were allocated to the stratum that contained the larger portion of the CCS. In this way, we obtain observed crop acreage by stratum.

Yield data come from the governments of Alberta, Saskatchewan, and Manitoba and are generally available for each major crop by soil region. For strata 26–29, we use the Government of Alberta's AgriProfit$ Benchmark Analysis.[6] For strata 30–35, the Government of Saskatchewan provides yields by crop for each rural municipality (RM).[7] The RM data are aggregated to the stratum level to obtain the yield data per stratum. For strata 36–40 in Manitoba, yield data are available by crop and by crop insurance risk area, which we match to each stratum.[8] We also require historical data for crop yields when we estimate the climate-crop regression equation (14) specified below. For Alberta and Manitoba, historical data were obtained through correspondence with relevant individuals in the respective agricultural ministries of these provinces.[9] In Saskatchewan, historic yield data by crop are available from their website (as indicated above).

For all seven crops, price data come from Statistics Canada (Cansim Table 002-0043) and variable cost data come from the three provincial governments. For strata 26–29, data are from the same source as the yield data. For strata 30–35, operating costs are from crop planning guides published by region by the Government of Saskatchewan.[10] For strata 36–40 (Manitoba), operating costs are only available for the whole province; these values are assumed to be the same for all strata.[11]

Pasture and Wetlands

Wetlands and pasture land are treated differently than land in crops, since no direct revenues accrue to wetlands or pasture. Information only pertains to observed areas in each activity: data on land in pasture come from the 2006 Census of Agriculture (Statistics Canada, 2007), while area of wetlands comes from the U.S. Fish and Wildlife Service's Waterfowl Population Survey. Pond counts are converted to acres using an average pond size of 0.85 acres (van Kooten, Whitey, and Wong, 2011). However, there are no value data for prices, yields, or variable costs for pasture or wetlands; we specify net returns by region for these activities to facilitate their inclusion in the model.

First, from a land-use standpoint, pasture provides benefits to farmers as an input into livestock production. Since we do not include livestock in the model, we simply assume that the value to farmers, regardless of region, is less than the net revenue to cropland. We assume a value of $5 per acre. In order to estimate the parameters in equation (8) and calibrate the PMP model, we also assume that "yield" is equal to 5 and "price" is equal to 1. The base-case model will calibrate to

---

[6] http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/econ10237. This website and others in this section were accessed March 15, 2011.

[7] http://www.agriculture.gov.sk.ca/rmyields.

[8] http://www.gov.mb.ca/agriculture/crops/cropproduction/gaa01d27.html.

[9] For Alberta, the most recent data are found at: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12891.

[10] http://www.agriculture.gov.sk.ca/crop-planning-guides.

[11] http://www.gov.mb.ca/agriculture/financial/farm2005/cac40s01.html

observed levels regardless of the value associated with pasture land. Thus, the actual value is not as important as the change in value relative to wetlands and crops due to climate change, which will depend on changes in land uses other than pasture.

Second, as discussed in the introduction, wetlands have been drained because they represent a net opportunity cost to private landowners, despite the fact that wetlands provide considerable social benefit. Meta-analyses by Woodward and Wui (2001) and Brander, Florax, and Vermaat (2006) estimate the benefits of the various ecological functions provided by wetlands. It is these benefits that the authority needs to consider because loss of wetlands imposes a cost on society as ecological values are forgone.

We consider how the inclusion of these benefits impacts decisions regarding land uses in the presence of climate change. The model is first solved from the government's perspective, in which wetlands have benefit to society. For comparison, it is then solved from the perspective of the private landowner, who does not take into account the externality costs of lost wetlands but only the net loss due to foregone agricultural production. Thus, we determine how internalizing the externality associated with wetlands will impact the management of wetlands in a drier climate, and how sensitive the solution is to the assumed value of wetland benefits. The value of wetlands to both the private landowner and society is determined as follows.

We assume the private landowner incurs a variable cost of providing wetlands area equal to the revenue forgone had the land been cropped plus the nuisance cost of providing wetlands (mainly avoiding wet areas during machine operations). From Cortus et al. (2011) and van Kooten, Whitey, and Wong (2011), the annual cost of providing wetlands ranges from \$25–\$65 per acre. Since the opportunity cost of cropped land is captured in the current model by the net returns to cropping, the actual cost of wetlands represents nuisance cost and will be very small. van Kooten, Whitey, and Wong (2011) employ a marginal cost of wetlands of \$47 per acre, and the returns to cropping in the region are roughly \$42 per acre (Withey and van Kooten, 2013). Therefore, it is assumed that the landowner incurs an annual marginal cost of \$5 per acre for providing wetlands.

Private landowners receive little benefit from retaining wetlands compared to the costs they incur. From society's perspective, however, wetlands provide benefits related to water filtration and flood control, wildlife habitat, viewing values, greenhouse gas storage, waterfowl production, and so on (Brander, Florax, and Vermaat, 2006, p. 226). Cortus et al. (2011) adapt estimates from Belcher, Edwards, and Gray (2001) of the social benefit of wetlands in Saskatchewan. The estimates range between \$16 and \$51 per acre with a "best guess" of \$32 per acre. Based on Cortus et al.'s best guess, we choose \$35 per acre for the social value of wetlands in this study. This is likely the most reasonable estimate for our study region, which encompasses the locations considered by Belcher, Edwards, and Gray (2001).

To account for variation in wetland values across strata, we estimate how the value of wetlands varies in terms of waterfowl production. Historic data from the U.S. Fish and Wildlife Service (2010) indicate that wetlands produce between 0.81 and 6.14 ducks per acre across strata 26–40. Bioeconomic models estimate the shadow price of ducks based on their intrinsic value as well as their value to hunters. We use such estimates from the literature and conservatively assume a shadow price of \$2 per duck, so that the value of wetlands in producing ducks is \$1.6 to \$12.3 per acre.[12] Thus, the social returns to (benefits of) wetlands vary from \$36.60 to \$47.30 per acre. This range of values is consistent with values found in the literature. To calibrate the model, we choose a price of \$7 per acre and adjust the "yield" to achieve the value of wetlands given above. This is done for all strata.

---

[12] Hammack and Brown (1974) estimated a value to hunters of \$2.40 per duck; the estimate from van Kooten, Whitey, and Wong (2011) includes amenity values of ducks and is around \$9.

Projected Impact of Climate Change on Crop Yields and Wetlands

There exist various methods for estimating the effect of future climate change on crop yields and land use. The Ricardian approach estimates an empirical relation between land rents and climate factors and has been used in some studies to estimate the climate change impacts on land use in Canada (Brklacich et al., 1994, 1999; Weber and Hauer, 2003).[13] Alternatively, detailed crop-growth models—such as EPIC, CERES and CROPGRO—simulate crop response to solar radiation, maximum and minimum temperatures, and precipitation, usually using a daily time step (e.g., Rosenzweig and Tubiello, 1996; Brassard and Singh, 2008). However, neither of the forgoing approaches is suitable for our purposes. The Ricardian approach does not provide specific estimates of crop yields (which we require), while crop-growth models require too much area-specific agronomic information (which is unavailable to us). As a result, we employ a panel-regression model that permits us to estimate climate change impacts on the yields of six crops plus wetlands area.

Panel-regression models are employed when one has time series data for multiple cross-sectional units (strata in our case). The general form of such models is given as

$$y_{it} = \alpha + \delta_i X_{it} + \varepsilon_{it},\ i = 1, \ldots, N;\ t = 1, \ldots, T, \tag{11}$$

where y_{it} is an (NT × 1) vector representing the dependent variable, is the intercept term, δ_i is a (K × 1) column vector of parameters to be estimated, X is an (NT × K) matrix of explanatory variables, and ε_{it} are the error terms. A common assumption in panel models is that

$$\varepsilon_{it} = v_i + u_{it}, \tag{12}$$

where v_i are unobserved individual-specific effects and u_{it} are i.i.d error terms. Panel models of this form are more efficient than standard OLS models. Further, by including the region-specific effects in the model, one picks up any time-invariant unobserved heterogeneity across regions. Thus, the δ_i parameters provide unbiased estimates of the effect of X on y, whereas similar OLS models would suffer from omitted-variable bias.

Based on statistical tests (see below), a fixed- as opposed to random-effects panel model is employed. In the fixed-effects (FE) model, the region-specific effect is a random variable that is allowed to be correlated with the explanatory variables. Including specification (12) and rewriting equation (11), the FE model is

$$y_{it} = (\alpha + v_i) + \delta_i X_{it} + u_{it}. \tag{13}$$

In this case, the v_i are considered region-specific, time-invariant effects that are fixed over time. The differences across regions can be captured by different intercepts for each region, that is, by interpreting the v_i as dummy variables. The model is then estimated using OLS. We also allow for period fixed effects in this model, d_t. Whereas regional fixed effects capture the unobserved impacts on yields that vary with region and not time, the period fixed effects capture impacts that vary with time and not region (i.e. technology, international price of wheat, etc.).

In the current context, we estimate the impact of precipitation and temperature on average crop yields for each crop in each stratum using the following FE specification:

$$y_{rit} = \delta_0 + \delta_1 T_{it} + \delta_2 T_{it}^2 + \delta_3 P_{it} + \delta_4 P_{it} \times T_{it} + b_i d_i + \eta_i d_t + u_{it}, \tag{14}$$

where y_{rit} is the observed average yield for crop r in region i at time t; T_{it} and P_{it} refer to the temperature and precipitation, respectively, affecting region i in time t; d_i are region-specific

---

[13] In a similar approach, Schlenker and Roberts (2009) focused on the impact of temperature on crop yields. Using this method, Robertson (2012) estimated a relation between temperatures and crop yields for the Canadian prairies. Three different versions of a temperature variable were calculated and used in alternative yield model formulations: average daily temperature, growing degree-days (GDDs), and Schlenker and Roberts' 1.8°F (1°C) intervals from 32°F (0°C) to 54°F (40°C). However, because these studies focus mainly on temperature and employ a very fine grid (Robertson employed nearly 8,000 cells for the Canadian PPR), they cannot be adapted for our use.

dummies that capture the fixed effects, or the unobserved variables that affect yields differently by region; d_t are time specific dummies that capture the period fixed effects, or the unobserved variables that affect yields differently over time; $\delta_m (m = 0, \ldots, 4)$, η_i, and b_i are parameters to be estimated; and u_{it} are error terms. The individual and period-specific effects capture unobserved heterogeneity across strata and over time, such as input prices, soil characteristics, and farmers' preferences, technology, and, therefore, the δ provide unbiased estimates of the effect of climate on crop yields.

To estimate the impact of climate change on land use in equation (14), data on crop yields and climate variables are required by strata and over time. Historic yield data are available for most crops by region for the period 1955 to 2008, providing a cross section of fifteen regions and a time series of fifty-four years for each crop. The sources of these data are discussed in the earlier data section.

Precipitation and temperature data come from Environment Canada's historic weather information, found in the National Climate Data and Information Archive.[14] The annual maximum temperature is used in the regression because too high a temperature during the growing season could have a negative impact on crop yield. We use annual and not growing-season precipitation because precipitation during the period between fall harvest and spring planting (especially as snowfall) is important to crop growth in a region in which significant parts have historically been characterized by drought.

For each of the seven equations, we tested for redundant individual and period FEs using a Lagrange Multiplier test. In each case, we strongly reject the null hypothesis that the FE are redundant, indicating that the FE model is preferred to a pooled OLS model. Further, we used a Hausman test to determine whether FE or random effects were appropriate. In all cases, we rejected the null hypothesis of random effects at the 5% or 10% level of significance (depending on the land use), indicating that fixed effects is the preferred specification. Therefore, regression model (14) is estimated for each of the crop activities and wetlands using panel fixed effects.

We used the dummy variable approach to account for unobserved heterogeneity across regions. As a result, the effect of climate variables on yields is generalized across the entire PPR (we get the same slope in each region) and the intercept is adjusted up or down in each region. In this model, we also test whether the slope varies across regions by interacting regional dummy variables with temperature and precipitation. Whether or not these variables are statistically significant will reveal whether the effect of temperature and precipitation varies across region.

Regression results are reported in table 2. In general, the models perform quite well, with relatively high $\bar{R}^2$ values, and most estimated coefficients have the expected signs. Given the nonlinearity in the regression model, it is not possible to isolate the marginal impact of precipitation and temperature on yields. However, at mean historic values, precipitation has a positive marginal impact on yields, and (for the most part) maximum temperature has a negative impact because warmer conditions will put stress on plants and decrease crop yields. The effect of temperature and precipitation is significant at the 5% level for most crops. For all crops, the effect of temperature and precipitation on yields does not vary by region. That is, for both temperature and precipitation, the coefficients on each of the interaction terms (regional dummies interacted with climate variables) are statistically insignificant. Thus, these interaction terms are not included in the final model nor reported in table 2. For wetlands, only the effect of temperature varies by region; therefore, estimates of the interaction variables (temperature and regional dummies) are reported in table 2 for wetlands. Simulation results using the fitted models indicate that the impacts of climate change on yields are well within the range -35% to +66% found using agronomic models for the study region (see Intergovernmental Panel on Climate Change, 2007; Brklacich et al., 1999) and similar to the range of -10% to +2.5% found by Parry et al. (1999).

---

[14] http://www.climate.weatheroffice.gc.ca/Welcome_e.html (accessed September 10, 2011).

Table 2. Parameter Estimates for Climate Equations

Variable	Wheat[a]	Barley	Oats	Canola	Peas[b]	Wetland Area[c]	Hay Land[b]
Constant	45.32^{**}	56.43^{**}	66.68^{**}	35.70^{**}	32.92^{**}	$388,212.9^{**}$	4.39^{**}
Temp	-3.39^{**}	-3.08^{**}	-3.61^{**}	3.06^{**}	0.2	$-24,954.6^{**}$	-0.63^{*}
Temp^2	0.11^{**}	0.07	0.054^{**}	0.11^{**}	−0.1	–	0.024^{**}
Precip	-0.02^{**}	-0.017^{*}	−0.021	-0.013^{*}	−0.02	46.53	0.0002
Precip×Temp	0.004^{**}	0.004^{**}	0.006	0.003^{**}	0.003	–	0.00006
Strata dummy variables multiplied by temperature							
Stratum 27						16,755.0	
Stratum 28						$20,506.9^{*}$	
Stratum 29						15,463.2	
Stratum 30						−3,653.2	
Stratum 31						$-29,215.0^{**}$	
Stratum 32						$-44,199.1^{**}$	
Stratum 33						11,656.8	
Stratum 34						$-38,765.8^{**}$	
Stratum 35						−12,095.1	
Stratum 36						$20,541.4^{*}$	
Stratum 37						775.2	
Stratum 38						$23,117.0^{*}$	
Stratum 39						11,382.2	
Stratum 40						8,429.1	
Adjusted R^2	0.72	0.75	0.67	0.64	0.62	0.77	0.61
Observations	762	772	777	696	301	779	239

Notes: The dependent variable is yield (bu/ac), with the exception of wetlands, for which the dependent variable is area (ac). Single and double asterisks (*, **) indicate statistical significance at the 10% and 5% levels, respectively.

[a] Historic data on winter wheat yields separate from spring wheat were not available, so this regression combines spring and winter wheat yields.

[b] There are fewer observations for hay and dry peas, since yield data were not available for all strata; however, we generalize the results to the entire PPR.

[c] We use a simpler linear form for wetlands, based on statistical significant and previous studies.

Scenario Description

To determine the impact of climate change on wetlands in the PMP model, we assume an increase in temperature of 5.4°F (3°C) and a decrease in precipitation of 10% (see Larson, 1995; Johnson et al., 2005; Sorenson et al., 1998; Withey and van Kooten, 2013).[15] While (Johnson et al., 2005) also consider the case in which precipitation increases, we focus on the more interesting situation from a policy perspective, namely, a potential increase in future aridity. This might be representative of the prolonged droughts that characterized the region during the early 1600s, late 1700s, and mid-1800s (Stewart, 2006), with the lower precipitation directly reducing wetlands. However, in the results section, we also discuss the implications of a wetter climate within the context of our model.

Climate change affects crop yields and thereby leads landowners to reduce (or increase) wetlands area. This might be considered an indirect effect. We assume that landowners do not switch to irrigation, which would be highly unlikely in the study region in any event. Projected changes in crop yields are found using the regression results reported in table 2 and are provided for each stratum in table 3. Values in the table represent a decrease from the historic average measured in bushels per acre. For most crops in table 3, the climate change scenario we employ leads to a small decrease in crop yields due to warmer temperatures and drier conditions. The effect is similar for different crops and across different regions, although climate has a positive impact on wheat yields in the model. Further, canola yields increase marginally in six strata.

---

[15] Although projections from regional climate models could be used, this would add unnecessary complexity. Our approach is reasonable because temperature increases are likely to be relatively uniform across the study region, while the absolute change in precipitation, which plays a more important role, will vary across strata.

Table 3. Change in Crop Yields and Wetlands Area due to 5.4°F (3°C) Higher Temperatures and 10% Lower Precipitation, Percentage Change by Strata

Stratum	Wheat	Barley	Oats	Canola	Peas	Wetland Area	Hay Land
26	1.22	−2.49	−3.45	−0.39	−8.38	−20.42	−5.05
27	3.34	−2.26	−4.28	3.00	−8.38	−23.93	−4.91
28	4.09	−2.37	−5.61	5.13	−8.38	−18.07	8.71
29	10.05	1.06	−1.27	9.91	−8.38	−37.78	10.11
30	−2.65	−4.99	−5.92	−4.80	−9.31	−37.13	−32.63
31	−2.12	−4.39	−4.79	−5.19	−5.67	−42.67	−34.95
32	0.19	−4.25	−6.12	−1.34	−12.66	−49.02	−24.30
33	0.37	−4.89	−6.81	−0.41	−15.65	−44.59	−15.19
34	−0.86	−3.71	−4.34	−3.94	−6.18	−51.12	−31.79
35	3.54	−2.81	−4.81	2.53	−14.23	−50.12	−12.63
36	4.72	−0.23	−0.68	2.50	−4.35	−26.59	−13.29
37	1.51	−2.41	−3.19	−1.03	−5.62	−31.37	−13.29
38	2.16	−1.77	−1.79	0.97	−5.50	−18.41	−13.29
39	1.17	−3.20	−4.37	−1.67	−6.40	−33.41	−13.29
40	0.93	−2.60	−3.35	−1.35	−6.40	−38.42	−13.29

Notes: Projections are based on the estimated coefficients in table 2 and fixed-effects coefficients.

The direct effect of climate change on wetlands area occurs because a warmer and drier climate simply leads to fewer wetlands. We can use the regression results for wetlands area (as opposed to yield) (see table 2) to predict the percentage change in wetland area in each stratum under the future climate. Table 3 reveals that wetlands will be dramatically reduced due to warmer, drier conditions; the potential reduction in wetlands ranges from about 18% in strata 28 and 38 to more than 50% in strata 34 and 35, with the greatest wetlands loss occurring in Saskatchewan.

There is also an indirect effect associated with wetlands reduction. If marginal willingness to pay for wetlands is downward sloping, a reduction in wetland area increases their value, thereby increasing the social opportunity cost of converting wetland area to cropland. In that case, society would seek to protect more wetlands. Because we lack information on marginal willingness to pay, we take this indirect effect into account by increasing the value of wetlands compared to the base case.

Given projected climate change, we consider four scenarios that represent increasingly interdependent impacts on land use. In scenario #1, we consider only the effect that changes in crop yields have on wetlands conservation under a new climate regime. In this scenario, wetlands are assumed to have social benefit, but no change is made to wetlands use as a result of climate. We change the yields of planted crops in this scenario. Wetlands are solely impacted because the optimal planting of different crops or land uses is based on maximizing revenue; the value of wetlands increases relative to other crops as their yields decrease. In scenario #2 we examine the impact of climate change on wetlands themselves in addition to estimating the effect of climate on crop yields. In both cases, we look at the impacts for each subregion of the PPR, since climate change affects wetlands and crop yields differently in each stratum.

Scenario #3 examines the impact of policies that are meant to mitigate climate change, particularly Canada's Renewable Fuel Standard (RFS), which was implemented in May 2008. This policy requires diesel fuel to contain 2% renewable content by 2010 and 5% by 2015, which will increase the demand for canola oil and increase the net returns to planting canola. Mussell (2006) estimates that the price of canola will increase by $19 per metric ton for the 2% blend and by $200 per ton for the 5% blend. For the PMP model, the RFS policy thus represents a 7% increase in the price of canola for the 2% blend and a 75% increase for the 5% blend. Since the latter result seems quite high, we consider the impact of increasing the price of canola by 10%. Thus, scenario

#3 examines the direct effects of climate on wetland areas, the indirect effect on wetlands area from climate-induced changes in crop yields, and the indirect effect associated with the increased price of canola due to a biofuels mitigation policy.

Finally, scenario #4 is the same as scenario #3, except that we increase the social benefit of wetlands by 50% to reflect an increase in the marginal willingness to pay for wetlands as they are lost due to climate change. While the choice of 50% is arbitrary, results are not very sensitive to this parameter.

Climate Impact on Optimal Land Use and Wetlands Retention

We first compare our base-case results to actual 2006 observed land use and then use the model to determine optimal land use and wetlands retention under the climate regime discussed in the previous section. The three-stage PMP model was solved in GAMS. Parameter values for the quadratic yield functions are estimated following the PMP approach described above and are provided in table 4. The PMP modeling results are presented in table 5. The observed (2006) and base-case land uses are presented in the first two rows of table 5. A comparison indicates that the calibration is almost exact.[16]

The bottom five rows of table 5 provide the optimal land-use allocations under each of the four scenarios identified above. We incorporate the climate effects into the PMP model by adjusting parameter values in equation (8). In particular, we adjust the crop yields by the estimated changes due to climate change (found in table 3) as well as the price of canola. We also adjust the marginal yield values for wetlands to restrict the wetland acreage to the levels found in table 3. For each scenario, we include the social value of wetlands, but in scenario #3 we ignore the externality benefits of conserving wetlands and consider the case in which wetlands have value only to landowners; only private returns are considered, so wetlands retention represents a cost. This allows us to compare wetlands retention under a changed climate when the landowner takes into account externalities or considers only the private costs or benefits of retaining wetlands.

Several trends are discernible from the climate change effects in table 5. First, in terms of cropland, the changes modeled under scenario #1 suggest that a warmer climate has the most pronounced positive effect on spring wheat production, at the expense of significant reductions in plantings of peas and hay, and smaller but important declines in barley, oats, and even canola plantings. This is not surprising given the yield changes expected as a result of climate change (see table 3).

Total canola plantings may decline very slightly as a result of climate change, but plantings are boosted by 24% when biofuel policies increase the price of canola. Land in pasture also increases considerably; since most crop revenues decline due to climate change, fewer crops will be planted in the future, increasing the land in pasture.

Wetlands area is projected to increase by about 1% due to the decreased value of crops relative to wetlands (scenario #1), but wetlands are reduced by a total of 37% when the direct effect of climate change on wetlands is factored in (scenario #2), with 38% of this loss attributable to the direct impact of climate change on wetlands area. Thus, climate effects on wetlands will be mitigated by reductions in crop yields, but only slightly. The impact of an increase in the price of canola has little to no effect on wetlands (scenario #3), reducing wetlands by an additional 0.3%. This result is different from that of Withey and van Kooten (2013) for reasons discussed below. When we increase the social benefits of wetlands to account for the increased marginal willingness to pay for wetlands (the indirect effect of climate change), the loss in wetlands due to both climate and biofuel policies falls slightly to about 36%.

---

[16] Only one model result out of 135 (9 land uses × 15 strata) differed from the observed value by more than 10%, a total of 7 by more than 3%, 10 by more than 2% (9 of 15 values for land in hay differed from observed values by >2%), and 19 by more than 1%. A complete table is available as supplementary material at: http://web.uvic.ca/ repa/publications/ REPA%20working%20papers/JARESupplement.pdf

Table 4. Quadratic Yield Parameters

Stratum	Spring Wheat	Barley	Oats	Winter Wheat	Canola	Peas	Wetland Area	Hay Land	Pasture
Maximum yield, $\beta_i = y_i + \gamma_i x_i$									
26	53.95	62.82	102.93	54.20	37.14	35.45	11.43	75.23	5.80
27	49.95	58.82	84.93	48.20	37.14	35.45	11.51	95.23	5.80
28	59.45	75.26	84.93	58.45	47.68	42.45	11.89	110.62	5.80
29	59.45	75.26	84.93	58.45	47.68	42.45	11.59	102.92	5.80
30	45.45	68.44	99.60	41.56	43.43	50.20	11.03	102.92	5.80
31	45.45	68.44	93.60	37.70	39.43	36.20	10.79	102.92	5.80
32	29.95	49.56	62.40	55.95	30.24	35.45	12.27	102.92	5.80
33	31.20	49.19	83.67	40.25	19.50	26.00	11.79	105.39	9.00
34	33.45	62.44	71.60	49.45	35.43	32.20	9.87	102.92	5.80
35	37.70	53.63	63.70	51.50	23.87	29.00	10.79	105.39	9.00
36	72.70	88.07	138.27	50.70	61.35	36.40	9.23	102.92	5.80
37	64.70	86.07	136.27	66.70	55.35	49.45	11.73	102.92	5.80
38	78.70	108.07	176.27	80.70	65.35	55.45	12.33	102.92	5.80
39	62.70	56.07	94.27	44.70	37.35	37.45	10.99	102.92	5.80
40	62.70	94.07	178.27	64.70	55.35	39.45	10.83	102.92	5.80
Marginal yield, $\gamma_i = \lambda_2/(p_i \times x_i)$									
26	0.005	0.005	0.064	1.838	0.001	0.003	0.011	0.009	0.000
27	0.005	0.005	0.117	0.516	0.004	0.005	0.037	0.029	0.001
28	0.030	0.028	0.450	2.572	0.058	0.090	0.037	0.107	0.002
29	0.019	0.021	0.394	0.171	0.070	0.062	0.051	0.086	0.001
30	0.004	0.013	0.034	2.138	0.005	0.023	0.013	0.026	0.001
31	0.007	0.018	0.034	0.399	0.005	0.017	0.009	0.038	0.001
32	0.000	0.005	0.034	0.258	0.005	0.004	0.010	0.021	0.005
33	0.018	0.039	0.410	0.328	0.078	0.027	0.075	0.093	0.006
34	0.001	0.019	0.022	0.230	0.008	0.009	0.008	0.047	0.001
35	0.015	0.029	0.075	0.326	0.005	0.009	0.023	0.083	0.011
36	1.043	1.290	2.096	6.693	0.099	8.485	0.062	0.242	0.001
37	0.030	0.080	0.220	0.587	0.029	1.611	0.024	0.035	0.002
38	0.024	0.170	0.239	0.394	0.034	1.573	0.111	0.110	0.006
39	0.016	0.009	0.149	0.088	0.010	0.011	0.031	0.081	0.003
40	0.038	0.140	0.620	1.053	0.042	0.058	0.038	0.124	0.006

As discussed earlier, the results focus on one scenario: a warmer and drier climate. This is because we wished to determine how drier conditions will impact wetlands management in the PPR. If wetter conditions prevail, the wet conditions will offset the rise in temperature, and the climate effect on wetlands area is likely to be negligible (Withey and van Kooten, 2011, 2013). However, with wetter conditions, the negative effects of climate change on crop yields will not be as pronounced. In fact, climate change will likely have a positive impact on crop yields if a wetter climate prevails (Brklacich et al., 1994, 1999). The increased value of cropland in such a scenario will lead to a reduction in wetlands, rather than the 1% increase found in this study. Thus, increased temperature will lead to a loss in wetlands regardless of changes in precipitation. However, the degree to which climate will affect wetlands in the PPR depends on future precipitation more than temperatures in this drought prone region.

Finally, if the social value of wetlands is used as the basis for scenario #3, wetlands are projected to decline by 36–37% from current levels. However, if a private landowner ignores the externality effects of converting wetlands to cropland, wetlands area falls by about 74% from that observed

Table 5. Land Uses: Observed (2006), Calibrated PMP Model, and Climate Change Scenarios (1,000s of acres)

Scenarios	Spring Wheat	Barley	Oats	Winter Wheat	Canola	Peas	Wetland Area	Hay Land	Pasture
Observed	14,626	7,800	4,020	407	11,258	2,993	3,782	10,551	9,059
PMP Base	14,631	7,807	4,019	409	11,270	2,975	3,786	10,563	9,005
#1	15,792	7,032	3,753	433	11,113	1,816	3,837	8,703	11,747
#2	16,047	7,076	3,764	435	11,142	1,844	2,367	8,734	12,674
#3	15,849	6,986	3,754	433	13,712	1,826	2,355	8,671	10,700
#3 (private)	15,993	7,028	3,762	434	13,739	1,843	971	8,703	11,752
#4	15,841	6,984	3,753	433	13,711	1,825	2,435	8,670	10,639

Notes: For scenario #1, we employed the projected yield data provided in table 3. For scenario #2, we added an adjustment provided by the calibrated marginal yield parameter for wetlands (see table 2); the marginal yield parameter was adjusted in order to restrict wetland acreage because there is no "yield" from wetlands that is impacted by climate. Finally, to estimate the impacts under scenarios #3 and #4, we first added to the previous two scenarios the increase in the price of canola and then the increase in the value of wetlands. Finally, we distinguish an alternative scenario #3, in which externality benefits are excluded and decisions are based only on the private benefits and costs of wetlands retention (denoted "private").

Table 6. Projected Change in Land Uses from Base Case, by Strata, Scenario #3, Including Social Benefits of Wetlands (%)

Strata	Spring Wheat	Barley	Oats	Winter Wheat	Canola	Peas	Wetland Area	Hay Land	Pasture
26	2.6	−13.3	−4.8	2.5	65.7	−60.7	−20.8	−10.9	−22.4
27	9.4	−18.7	−7.9	10.3	93.1	14.1	−24.5	−7.6	−31.3
28	5.3	−5.2	−9.9	5.6	15.0	398.3	−18.1	7.4	−5.4
29	12.9	−2.6	−2.5	13.8	21.6	73.0	−38.0	10.4	−17.6
30	−4.3	−8.2	−8.0	−3.4	2.3	−100.0	−36.2	−33.0	92.9
31	−2.6	−6.7	−6.7	−1.1	2.7	−100.0	−41.2	−35.2	104.2
32	28.6	−13.1	−7.9	2.0	16.2	−38.6	−47.7	−23.6	122.1
33	0.6	−14.3	−7.3	1.2	9.9	−26.1	−44.6	−15.0	0.0
34	3.3	−6.6	−10.2	0.1	6.3	−33.7	−49.9	−32.1	92.8
35	5.9	−10.0	−8.0	10.4	64.0	−99.2	−50.1	−12.5	0.0
36	7.9	−0.5	−0.6	15.6	10.2	232.2	−26.5	−14.1	2.3
37	3.6	−4.1	−2.8	3.1	7.2	−100.0	−30.8	−13.5	34.8
38	3.2	−2.6	−1.4	2.9	7.4	−13.5	−18.5	−14.2	−6.4
39	3.2	−36.2	−5.3	8.5	18.3	−85.9	−32.8	−13.4	38.2
40	3.0	−3.7	−2.5	2.5	6.9	−100.0	−37.6	−13.1	55.0
Total	5.5	−9.7	−5.7	4.9	23.1	−2.7	−34.5	−14.7	30.6

today. This result shows how sensitive the results are to the value of wetlands while also highlighting the importance of internalizing the economic externality associated with wetlands management.

The percentage changes in land allocation for each of the fifteen strata under scenario #3 are provided in table 6; in this scenario, the private landowner is incentivized to take into account the social values of wetlands. A summary of the reduction in wetlands under this scenario is provided in table 7. Results confirm those of table 5. The largest increase in land use triggered by predicted global warming is in canola and pasture land, while the largest decreases are in wetlands area. Other land uses are expected to experience marginal increases or declines. We focus the rest of this discussion on how wetlands losses compare across strata.

The loss in wetlands across regions in the PPR ranges by stratum from about 18% to 50% (table 6), or 9,000 to 278,000 acres (table 7). Unsurprisingly, the effect of climate change and mitigation policies on wetlands is not homogeneous across regions, because precipitation and soil characteristics (which impact crop yields) differ significantly across western Canada's grain belt. In

Table 7. Original Level of Wetlands and Projected Wetlands under Scenario #3 with Social Benefits of Wetlands Included, by Strata (1,000s of acres)

Stratum	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	Total
Base Case	459	140	145	103	388	532	542	74	557	221	65	223	50	158	128	3,786
Scenario #3	364	106	119	64	248	312	283	41	279	110	48	154	41	106	80	2,355

table 6, the largest proportional declines in wetlands are in strata 29 through 35 and 40, while the largest decreases in wetlands area are in strata 31, 32, and 34 (table 7 and figure 1). Thus, wetlands loss is greatest in percentage terms in southern Alberta (stratum 29), southern Saskatchewan (strata 30–35), and southwestern Manitoba (stratum 40).

In the land-use model, changes in wetlands in each stratum are driven primarily by the predicted climate effect on wetlands area as determined from the relation in table 3. However, the social benefits of wetlands and the opportunity cost of retaining them are given by the net returns to other land uses in the region; this also affects wetlands loss. Further, the net returns to other crops are impacted by climate-induced changes in crop yields and via the increased price of canola resulting from biofuel policies. Overall, therefore, there is a direct climate impact on wetlands and an indirect impact resulting from changes in net returns to cropping. Based on these factors, we can identify the potential drivers of the provincial patterns of wetlands loss as indicated in tables 6 and 7. In doing so, it is helpful to consult figure 1.

The largest actual reduction in wetlands area is projected to occur in Saskatchewan. This is due in part to the fact that the largest areas of wetlands are found in Saskatchewan; however, the largest proportional declines are also projected to occur in Saskatchewan, particularly in the southern strata. The declines in wetlands in these strata are driven by severe climate impacts (table 7); changes in crop yields due to climate change in these strata are not substantially different from other regions. While proportional wetlands losses are larger than the PPR average in all strata of Saskatchewan, the largest losses are in strata 32–35, which are the most southern strata.

Wetlands loss in Alberta (strata 26–39) is projected to total 24%, the smallest proportional wetland loss of the three provinces. There is very little reduction in wetlands in northern areas; while increased canola plantings are projected for strata 26 and 27, this comes at the cost of other crops rather than wetlands. Climate effects on wetlands in the most southern strata are above the regional average, which is not surprising since this is an arid area within the PPR.

Finally, the overall projected reduction in wetlands in Manitoba is 31%. The proportional loss of wetlands is the smallest in eastern and northern strata (36–38), whereas the southwestern strata are the most susceptible to climate change, with losses above regional averages.

Discussion

This application employed positive mathematical programming to calibrate land use to observed acreage in the Canadian prairie pothole region and to estimate the impact of climate change on wetlands. A calibrated model consisting of fifteen regions and nine land uses per region was used to project a reduction of wetlands of 18–50% from observed 2006 levels in different strata as a result of a warmer and drier climate, with an overall decline of about 36%. If the externality benefits of wetlands are ignored, however, the effects of climate change on wetlands are even more severe, with as much as 75% of current wetlands in the region potentially being lost.

The impact of climate change on wetlands in this study is quite different from that in Withey and van Kooten (2013), who used an optimal control model to address a similar question. The direct climate impact on wetlands is more significant in this study and more in line with previous studies (Larson, 1995; Sorenson et al., 1998), while the impact of biofuel policies on wetlands in Canada's prairie pothole region is significantly smaller. Withey and van Kooten (2013) found that biofuel policies have a major negative impact on wetlands retention, whereas this study finds the impact to be negligible. There are two explanations for the different results. First, while Withey and van Kooten estimated a nonlinear (logistics) state equation relating climate to wetlands, we estimated a linear functional form with panel fixed-effects. Second, to keep the analytic model simple and tractable, Withey and van Kooten assumed only two land uses (wetlands and cropland); increases in cropland due to biofuel policies could only come at the expense of wetlands. In this study, we used a richer model of land use that explicitly modeled the tradeoffs among all major crops and land uses in the region. We found that wetlands acreage will not necessarily be reduced under biofuel policies (which raise canola prices); rather, landowners might substitute away from other crops. Thus, biofuel policies might not further exacerbate the wetlands loss occurring solely as a result of a changed climate.

In the current study, we find the impacts on wetlands are not homogeneous across regions, as the largest wetlands losses are projected to occur in south-central Saskatchewan, southern Alberta, and southwestern Manitoba. With drier conditions, it will be optimal to have more wetlands in northeast Manitoba and the northern regions of Saskatchewan and Alberta. In our models, the warming-induced shift in wetlands in western Canada's grain belt, the prairie pothole region, is toward the northern and eastern regions. This is consistent with projections by Johnson et al. (2005), who also find that, relative to current conditions, the most productive waterfowl habitat will shift from southwestern Saskatchewan to the northern and eastern fringes if a warmer, drier climate prevails in the twenty-first century.

The current research provides a framework for understanding how climate change will affect land use in western Canada because it analyzes the tradeoffs among all major land uses. It also provides guidance for policymakers. First, whether the externality benefits of wetlands are taken into account will have serious implications for wetlands management. Policies need to internalize the externality benefits of wetlands by providing payments to landowners for retaining wetlands. Second, since global warming could severely reduce wetlands area, policymakers need to implement plans in a timely fashion to minimize losses.

Based on this analysis, it is clear that the largest decreases in wetlands will be in Saskatchewan. Yet it will still be optimal to have more wetlands in Saskatchewan than in Alberta or Manitoba despite potentially significant losses in the former. Given that climate change will have the greatest impact on wetlands in southern Saskatchewan, decision makers may wish to devote more effort to protecting wetlands in that province than in Alberta or Manitoba. Further, given the shift in productive wetlands from south to northeast, it may be necessary to target wetlands protection in Manitoba and northern Alberta as well. However, it remains an open question as to whether Manitoba can make up for lost wetlands in Saskatchewan.

[Received May 2013; final revision received January 2014.]

References

Belcher, K., C. K. Edwards, and B. Gray. “Ecological Fiscal Reform and Agricultural Landscapes, Analysis of Economic Instruments: Conservation Cover Incentive Program.” Background paper, National Roundtable on the Economy and Environment, Ottawa, Ontario, 2001.

Brander, L. M., R. J. G. M. Florax, and J. E. Vermaat. “The Empirics of Wetland Valuation: A Comprehensive Summary and a Meta-Analysis of the Literature.” *Environmental and Resource Economics* 33(2006):223–250.

Brassard, J., and B. Singh. “Impacts of Climate Change and CO2 Increase on Agricultural Production and Adaptation Options for Southern Québec, Canada.” *Mitigation and Adaptation Strategies for Global Change* 13(2008):241–265.

Brklacich, M., C. Bryant, B. Veenhof, and A. Beauchesne. “Implications of Global Climatic Change for Canadian Agriculture: A Review and Appraisal of Research from 1984–1997.” In *Canada Country Study: Climate Impacts and Adaptation,* Ottawa, Ontario: Environment Canada, 1999, 220–256.

Brklacich, M., R. Stewart, V. Kirkwood, and R. Muma. “Effects of Global Climate Change on Wheat Yields in the Canadian Prairie.” In C. Rosenzweig, A. Iglesias, R. Benioff, and J. Smith, eds., *Implications of Climate Change for International Agriculture: Crop Modeling Study,* Washington, DC: U.S. Environmental Protection Agency, 1994, 1–23.

Brown, G. M., and J. Hammack. “Dynamic Economic Management of Migratory Waterfowl.” *Review of Economics and Statistics* 55(1973):73–82.

Brown, G. M., J. Hammack, and M. F. Tillman. “Mallard Population Dynamics and Management Models.” *Journal of Wildlife Management* 40(1976):542–555.

Cortus, B. G., S. R. Jeffrey, J. R. Unterschultz, and P. C. Boxall. “The Economics of Wetland Drainage and Retention in Saskatchewan.” *Canadian Journal of Agricultural Economics* 59(2011):109–126.

de Frahan, B. H., J. Buysse, P. Polome, B. Fernagut, O. Harmignie, L. Lauwers, G. van Huylenbroeck, and J. van Meensel. “Positive Mathematical Programming for Agricultural and Environmental Policy Analysis: Review and Practice.” In A. Weintraub, et al., ed., *Handbook of Operations Research in Natural Resources,* No. 99 in International Series in Operations Research & Management Science. New York: Springer Science, 2007, 129–154.

Hammack, J., and G. M. Brown. *Waterfowl and Wetlands: Toward Bioeconomic Analysis.* Washington, DC: Resources for the Future, 1974.

Heckelei, T., W. Britz, and Y. Zhang. “Positive Mathematical Programming Approaches - Recent Developments in Literature and Applied Modelling.” *Bio-Based and Applied Economics* 1(2012):109–124.

Howitt, R. E. “Positive Mathematical Programming.” *American Journal of Agricultural Economics* 77(1995):329–342.

Intergovernmental Panel on Climate Change. *Climate Change 2007: The Physical Science Basis.* Cambridge, UK: Cambridge University Press, 2007.

Johnson, F. A., C. T. Moore, W. L. Kendall, and J. A. Dubovsky. “Uncertainty and the Management of Mallard Harvests.” *Journal of Wildlife Management* 61(1997):202–216.

Johnson, W. C., B. V. Millett, T. Gilmanov, and R. A. Voldseth. “Vulnerability of Northern Prairie Wetlands to Climate Change.” *Bioscience* 55(2005):863–872.

Johnson, W. C., B. Werner, G. R. Guntenspergen, and R. A. Voldseth. “Prairie Wetland Complexes as Landscape Functional Units in a Changing Climate.” *BioScience* 60(2010):128–140.

Larson, D. L. “Effects of Climate on Numbers of Northern Prairie Wetlands.” *Climatic Change* 30(1995):169–180.

Mitsch, W. J., and J. G. Gosselink. *Wetlands.* Hoboken, NJ: Wiley , 2007, 4th ed.

Mussell, A. *Effect of Mandated Biodiesel Blend on Canadian Canola*. Guelph, Ontario: George Morris Centre for Policy Analysis, 2006. Available online at http://www.canolacouncil.org/media/505206/al_mussell_pres.pdf.

Ojima, D. S., and J. M. Lackett. "Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change." A Report of the Central Great Plains Regional Assessment Group for the U.S. Global Change Research Program, Central Great Plains Steering Committee and Assessment Team, Colorado State University, Fort Collins, CO, 2002.

Paris, Q. *Economic Foundations of Symmetric Programming*. Cambridge, UK: Cambridge University Press, 2011.

Parry, M., C. Rosenzweig, A. Iglesias, G. Fischer, and M. Livermore. "Climate Change and World Food Security: A New Assessment." *Global Environmental Change* 9(1999):S51–S67.

Prairie Habitat Joint Venture. *Prairie Habitat Joint Venture: Implementation Plan 2007–2012*. Edmonton, Alberta: Environment Canada, 2008. Revised May 2009. Available online at http://www.phjv.ca/pdf/PHJV%20Implementation%20Plan%20090506-lowres.pdf.

Robertson, S. M. *A Spatial Model of Agricultural Land Use with Climate Change for the Canadian Prairies*. Ph.D. dissertation, Department of Resource Economics and Environmental Sociology, University of Alberta, Edmonton, Alberta, 2012.

Rosenzweig, C., and F. Tubiello. "Effects of Changes in Minimum and Maximum Temperature on Wheat Yields in the Central U.S.: A Simulation Study." *Agricultural and Forest Meteorology* 80(1996):215–230.

Schlenker, W., and M. J. Roberts. "Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change." *Proceedings of the National Academy of Sciences of the United States of America* 106(2009):15,594–15,598.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T. Yu. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change." *Science* 319(2008):1238–1240.

Sorenson, L. G., R. Goldberg, T. L. Root, and M. G. Anderson. "Potential Effects of Global Warming on Waterfowl Populations Breeding in the Northern Great Plains." *Climatic Change* 40(1998):343–369.

Statistics Canada. "2006 Census of Agriculture." 2007. Available online at http://www.statcan.gc.ca/ca-ra2006/index-eng.htm.

Stewart, I. "Drought." In *The Encyclopedia of Saskatchewan: A Living Legacy,* Regina, Saskatchewan: Canadian Plains Research Center, University of Regina, 2006. Available online at http://esask.uregina.ca/entry/drought.html.

U.S. Fish and Wildlife Service. *Waterfowl Breeding Population & Habitat Survey Strata Estimate Data*. Washington, DC: Division of Migratory Bird Management, Migratory Bird Data Center, 2010. Available online at http://migbirdapps.fws.gov/ and http://www.fws.gov/migratorybirds.

van Kooten, G. C., P. Whitey, and L. Wong. "Bioeconomic Modelling of Wetlands and Waterfowl in Western Canada: Accounting for Amenity Values." *Canadian Journal of Agricultural Economics* 59(2011):167–183.

Weber, M., and G. Hauer. "A Regional Analysis of Climate Change Impacts on Canadian Agriculture." *Canadian Public Policy* 29(2003):163–180.

Withey, P., and G. C. van Kooten. "The Effect of Climate Change on Optimal Wetlands and Waterfowl Management in Western Canada." *Ecological Economics* 70(2011):798–805.

———. "The Effect of Climate Change on Wetlands and Waterfowl in Western Canada: Incorporating Cropping Decisions into a Bioeconomic Model." *Natural Resource Modeling* 26(2013):305–330.

Woodward, R. T., and Y. Wui. "The Economic Value of Wetland Services: A Meta-Analysis." *Ecological Economics* 37(2001):257–270.