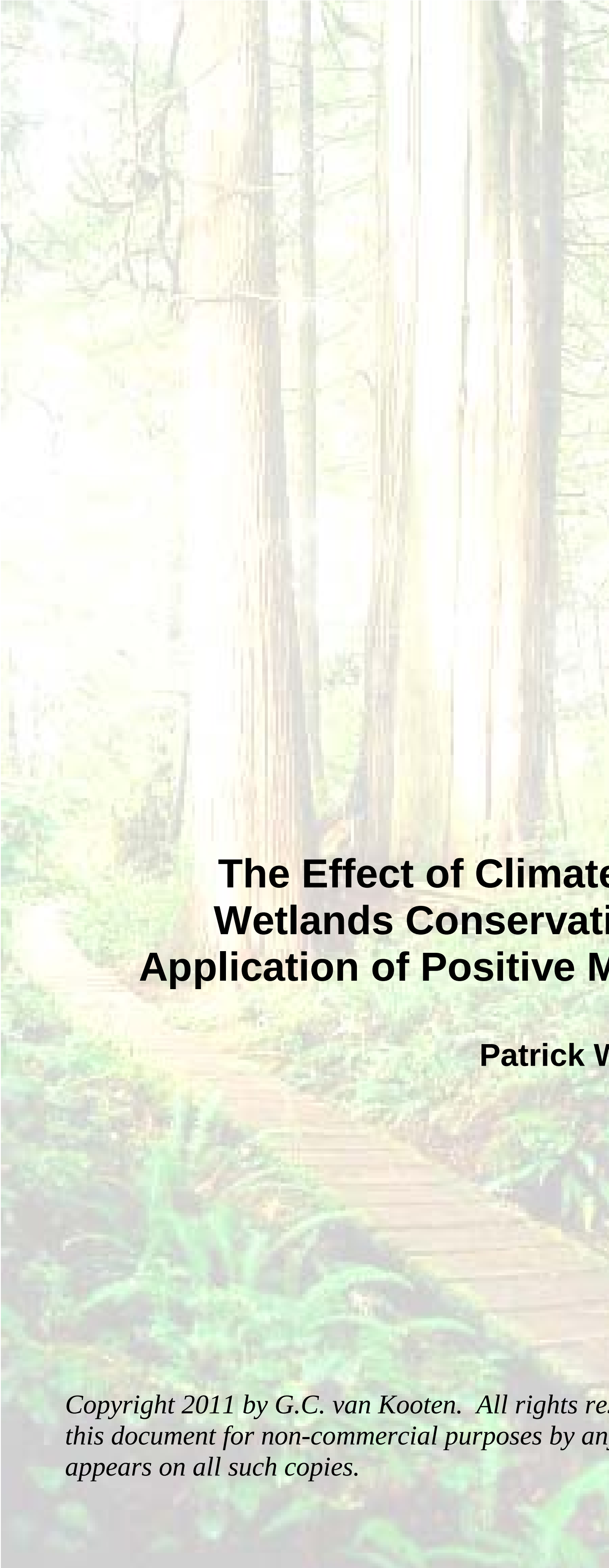

WORKING PAPER
2011-04

REPA

Resource Economics
& Policy Analysis
Research Group

Department of Economics
University of Victoria

The Effect of Climate Change on Land Use and Wetlands Conservation in Western Canada: An Application of Positive Mathematical Programming

Patrick Withey and G. Cornelis van Kooten

June 2011

REPA Working Papers:

2003-01 – Compensation for Wildlife Damage: Habitat Conversion, Species Preservation and Local Welfare (Rondeau and Bulte)
2003-02 – Demand for Wildlife Hunting in British Columbia (Sun, van Kooten and Voss)
2003-03 – Does Inclusion of Landowners' Non-Market Values Lower Costs of Creating Carbon Forest Sinks? (Shaikh, Suchánek, Sun and van Kooten)
2003-04 – Smoke and Mirrors: The Kyoto Protocol and Beyond (van Kooten)
2003-05 – Creating Carbon Offsets in Agriculture through No-Till Cultivation: A Meta-Analysis of Costs and Carbon Benefits (Manley, van Kooten, Moeltne, and Johnson)
2003-06 – Climate Change and Forest Ecosystem Sinks: Economic Analysis (van Kooten and Eagle)
2003-07 – Resolving Range Conflict in Nevada? The Potential for Compensation via Monetary Payouts and Grazing Alternatives (Hobby and van Kooten)
2003-08 – Social Dilemmas and Public Range Management: Results from the Nevada Ranch Survey (van Kooten, Thomsen, Hobby and Eagle)
2004-01 – How Costly are Carbon Offsets? A Meta-Analysis of Forest Carbon Sinks (van Kooten, Eagle, Manley and Smolak)
2004-02 – Managing Forests for Multiple Tradeoffs: Compromising on Timber, Carbon and Biodiversity Objectives (Krcmar, van Kooten and Vertinsky)
2004-03 – Tests of the EKC Hypothesis using CO2 Panel Data (Shi)
2004-04 – Are Log Markets Competitive? Empirical Evidence and Implications for Canada-U.S. Trade in Softwood Lumber (Niquidet and van Kooten)
2004-05 – Conservation Payments under Risk: A Stochastic Dominance Approach (Benítez, Kuosmanen, Olschewski and van Kooten)
2004-06 – Modeling Alternative Zoning Strategies in Forest Management (Krcmar, Vertinsky and van Kooten)
2004-07 – Another Look at the Income Elasticity of Non-Point Source Air Pollutants: A Semiparametric Approach (Roy and van Kooten)
2004-08 – Anthropogenic and Natural Determinants of the Population of a Sensitive Species: Sage Grouse in Nevada (van Kooten, Eagle and Eiswerth)
2004-09 – Demand for Wildlife Hunting in British Columbia (Sun, van Kooten and Voss)
2004-10 – Viability of Carbon Offset Generating Projects in Boreal Ontario (Biggs and Laaksonen-Craig)
2004-11 – Economics of Forest and Agricultural Carbon Sinks (van Kooten)
2004-12 – Economic Dynamics of Tree Planting for Carbon Uptake on Marginal Agricultural Lands (van Kooten) (Copy of paper published in the Canadian Journal of Agricultural Economics 48(March): 51-65.)
2004-13 – Decoupling Farm Payments: Experience in the US, Canada, and Europe (Ogg and van Kooten)
2004–14– Afforestation Generated Kyoto Compliant Carbon Offsets: A Case Study in Northeastern Ontario (Biggs)
2005–01– Utility-scale Wind Power: Impacts of Increased Penetration (Pitt, van Kooten, Love and Djilali)
2005–02 –Integrating Wind Power in Electricity Grids: An Economic Analysis (Liu, van Kooten and Pitt)
2005–03 –Resolving Canada-U.S. Trade Disputes in Agriculture and Forestry: Lessons from Lumber (Biggs, Laaksonen-Craig, Niquidet and van Kooten)

2005–04–Can Forest Management Strategies Sustain the Development Needs of the Little Red River Cree First Nation? (Krcmar, Nelson, van Kooten, Vertinsky and Webb)
2005–05–Economics of Forest and Agricultural Carbon Sinks (van Kooten)
2005–06– Divergence Between WTA & WTP Revisited: Livestock Grazing on Public Range (Sun, van Kooten and Voss)
2005–07 –Dynamic Programming and Learning Models for Management of a Nonnative Species (Eiswerth, van Kooten, Lines and Eagle)
2005–08 –Canada-US Softwood Lumber Trade Revisited: Examining the Role of Substitution Bias in the Context of a Spatial Price Equilibrium Framework (Mogus, Stennes and van Kooten)
2005–09 –Are Agricultural Values a Reliable Guide in Determining Landowners' Decisions to Create Carbon Forest Sinks?* (Shaikh, Sun and van Kooten) *Updated version of Working Paper 2003-03
2005–10 –Carbon Sinks and Reservoirs: The Value of Permanence and Role of Discounting (Benitez and van Kooten)
2005–11 –Fuzzy Logic and Preference Uncertainty in Non-Market Valuation (Sun and van Kooten)
2005–12 –Forest Management Zone Design with a Tabu Search Algorithm (Krcmar, Mitrovic-Minic, van Kooten and Vertinsky)
2005–13 –Resolving Range Conflict in Nevada? Buyouts and Other Compensation Alternatives (van Kooten, Thomsen and Hobby) *Updated version of Working Paper 2003-07
2005–14 –Conservation Payments Under Risk: A Stochastic Dominance Approach (Benítez, Kuosmanen, Olschewski and van Kooten) *Updated version of Working Paper 2004-05
2005–15 –The Effect of Uncertainty on Contingent Valuation Estimates: A Comparison (Shaikh, Sun and van Kooten**)**
2005–16 –Land Degradation in Ethiopia: What do Stoves Have to do with it? (Gebreegziabher, van Kooten and.van Soest)
2005–17 –The Optimal Length of an Agricultural Carbon Contract (Gulati and Vercammen)
2006–01 –Economic Impacts of Yellow Starthistle on California (Eagle, Eiswerth, Johnson, Schoenig and van Kooten)
2006–02 -The Economics of Wind Power with Energy Storage (Benitez, Dragulescu and van Kooten)
2006–03 –A Dynamic Bioeconomic Model of Ivory Trade: Details and Extended Results (van Kooten)
2006–04 –The Potential for Wind Energy Meeting Electricity Needs on Vancouver Island (Prescott, van Kooten and Zhu)
2006–05 –Network Constrained Wind Integration: An Optimal Cost Approach (Maddaloni, Rowe and van Kooten)
2006–06 –Deforestation (Folmer and van Kooten)
2007–01 –Linking Forests and Economic Well-being: A Four-Quadrant Approach (Wang, DesRoches, Sun, Stennes, Wilson and van Kooten)
2007–02 –Economics of Forest Ecosystem Forest Sinks: A Review (van Kooten and Sohngen)
2007–03 –Costs of Creating Carbon Offset Credits via Forestry Activities: A Meta-Regression Analysis (van Kooten, Laaksonen-Craig and Wang)
2007–04 –The Economics of Wind Power: Destabilizing an Electricity Grid with Renewable Power (Prescott and van Kooten)
2007–05 –Wind Integration into Various Generation Mixtures (Maddaloni, Rowe and van Kooten)
2007–06 –Farmland Conservation in The Netherlands and British Columbia, Canada: A Comparative Analysis Using GIS-based Hedonic Pricing Models (Cotteleer, Stobbe and van Kooten)

2007–07 –Bayesian Model Averaging in the Context of Spatial Hedonic Pricing: An Application to Farmland Values (Cotteleer, Stobbe and van Kooten)
2007–08 –Challenges for Less Developed Countries: Agricultural Policies in the EU and the US (Schure, van Kooten and Wang)
2008–01 –Hobby Farms and Protection of Farmland in British Columbia (Stobbe, Eagle and van Kooten)
2008-01A-Hobby Farm's and British Columbia's Agricultural Land Reserve (Stobbe, Eagle, Cotteleer and van Kooten)
2008–02 –An Economic Analysis of Mountain Pine Beetle Impacts in a Global Context (Abbott, Stennes and van Kooten)
2008–03 –Regional Log Market Integration in New Zealand (Niquidet and Manley)
2008–04 –Biological Carbon Sequestration and Carbon Trading Re-Visited (van Kooten)
2008–05 –On Optimal British Columbia Log Export Policy: An Application of Trade theory (Abbott)
2008–06 –Expert Opinion versus Transaction Evidence: Using the Reilly Index to Measure Open Space premiums in the Urban-Rural Fringe (Cotteleer, Stobbe and van Kooten)
2008–07 –Forest-mill Integration: a Transaction Costs Perspective (Niquidet and O'Kelly)
2008–08 –The Economics of Endangered Species Poaching (Abbott)
2008–09 –The Ghost of Extinction: Preservation Values and Minimum Viable Population in Wildlife Models (van Kooten and Eiswerth)
2008–10 –Corruption, Development and the Curse of Natural Resources (Pendergast, Clarke and van Kooten)
2008–11 –Bio-energy from Mountain Pine Beetle Timber and Forest Residuals: The Economics Story (Niquidet, Stennes and van Kooten)
2008-12 –Biological Carbon Sinks: Transaction Costs and Governance (van Kooten)
2008-13 –Wind Power Development: Opportunities and Challenges (van Kooten and Timilsina)
2009-01 –Can Domestication of Wildlife Lead to Conservation? The Economics of Tiger Farming in China (Abbott and van Kooten)
2009-02 – Implications of Expanding Bioenergy Production from Wood in British Columbia: An Application of a Regional Wood Fibre Allocation Model (Stennes, Niquidet and van Kooten)
2009-03 – Linking Matlab and GAMS: A Supplement (Wong)
2009-04 – Wind Power: The Economic Impact of Intermittency (van Kooten)
2009-05 – Economic Aspects of Wind Power Generation in Developing Countries (van Kooten and Wong)
2009-06 – Niche and Direct Marketing in the Rural-Urban Fringe: A Study of the Agricultural Economy in the Shadow of a Large City (Stobbe, Eagle and van Kooten)
2009-07 – The Economics and Policy of Global Warming (van Kooten, Beisner and Geddes)
2010-01 – The Resource Curse: A State and Provincial Analysis (Olayele)
2010-02 – Elephants and the Ivory Trade Ban: Summary of Research Results (van Kooten)
2010-03 – Managing Water Shortages in the Western Electricity Grids **(**Scorah, Sopinka and van Kooten)
2010-04 - Bioeconomic modeling of wetlands and waterfowl in Western Canada: Accounting for amenity values (van Kooten, Withey and Wong)
2010-05 – Waterfowl Harvest Benefits in Northern Aboriginal Communities and Potential Climate Change Impacts (Krcmar**,** van Kooten and Chan-McLeod)
2011-01 – The Impact of Agriculture on Waterfowl Abundance: Evidence from Panel Data (Wong**,** van Kooten and Clarke)

2011-02 – Economic Analysis of Feed-in Tariffs for Generating Electricity from Renewable Energy Sources (van Kooten)

2011-03 – Climate Change Impacts on Waterfowl Habitat in Western Canada (van Kooten, Withey and Wong)

2011-04 – The Effect of Climate Change on Land Use and Wetlands Conservation in Western Canada: An Application of Positive Mathematical Programming (Withey and van Kooten)

For copies of this or other REPA working papers contact:
REPA Research Group
Department of Economics
University of Victoria PO Box 1700 STN CSC Victoria, BC V8W 2Y2 CANADA
Ph: 250.472.4415
Fax: 250.721.6214
www.vkooten.net/repa

The Effect of Climate Change on Land Use and Wetlands Conservation in Western Canada: An Application of Positive Mathematical Programming

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

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

* Department of Economics, University of Victoria,

June 1, 2011

Abstract

This study examines the impact of climate change on land use in the Prairie Pothole Region of Western Canada, with particular emphasis on how climate change will impact wetlands. A multi-region Positive Mathematical Programming model calibrates land use in the area to observed acreage in 2006. Policy simulations for both climate effects as well as the effects of biofuel policies determine how climate change will affect land use and wetlands. Given that the model calibrates to observed acreage, the policies provide a realistic view of how land use might change from current levels, given the effects of climate change. Results indicate that climate change could decrease wetlands in this area by as much as 50 percent. The effect will be very different depending on whether or not the social benefits of wetlands are considered, and the effects of climate change on wetlands are heterogeneous across the Prairie Provinces.

Key Words: Positive mathematical programming; wetlands conservation; land use change; climate change; biofuels; Prairie pothole region

JEL categories: C02; C63; Q15; Q54; Q57; Q24; Q25

1. Introduction

Wetlands are among the world's most important ecosystems, alternately referred to as the 'kidneys of the landscape' or a region's '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 have significant economic value to society. Nonetheless, wetlands in the Prairie Pothole Region (PPR) of Western Canada have been and continue to be drained due to agricultural development. Given that the social benefits of wetlands do not typically accrue to landowners, it is not surprising that they continue to be converted to agricultural production.

In addition to the risk that farmers drain wetlands in the PPR, they are also threatened by climate change. First, a potentially drier climate in the coming century could reduce wetlands significantly (Johnson et al. 2005). Climate assessments predict that air temperatures in the region could rise by between 1.8^{o}C and 4.0^{o}C by 2100 (IPCC 2007; Johnson et al. 2010), and that changes in average annual precipitation during the next 100 years may vary between a decrease of 20% and an increase of 20% (Johnson et al. 2005). Second, policies that seek to mitigate climate change by subsidizing the production of crops used for biofuels will decrease the value of wetlands relative to agricultural land, which will further increase the incentive to drain wetlands.

Given the significant benefits provided by wetlands in the PPR, both from the waterfowl that are produced (and hunted) and the ecosystem amenity values of wetlands (van Kooten et al. 2010), it is essential that this resource is managed to optimize social welfare over time and it is important to understand how climate change might impact wetlands management. The objectives of the current research are to: (1) investigate the possible effect that projected future aridity will have on wetlands in the study region (Figure 1); (2) examine the impact that climate mitigation policies will have on wetlands; (3) consider the divergence in optimal land use between the private landowner and the social planner (who considers the externality benefits of wetlands); and (4) determine how climate change affects wetlands across the heterogeneous regions of the PPR.

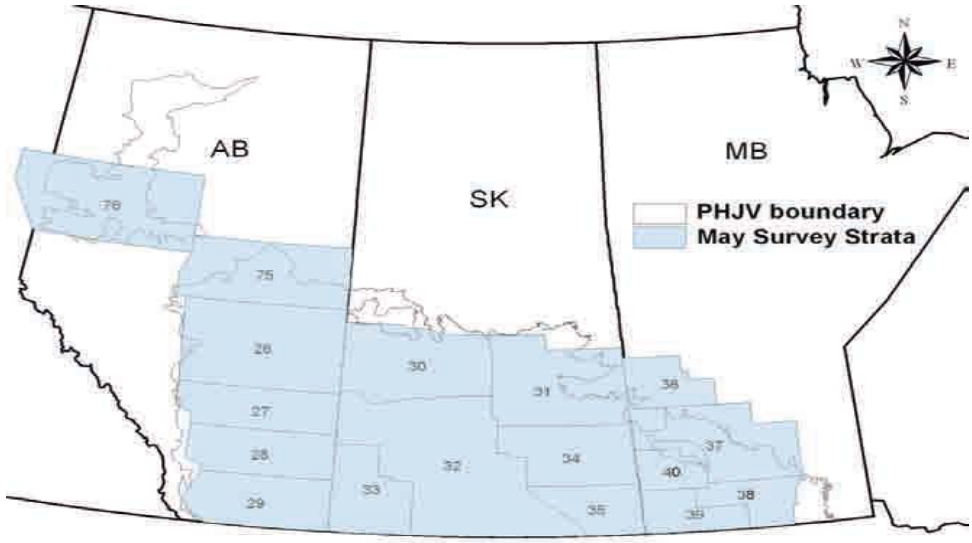

Figure 1: US Fish and Wildlife Service May Survey Strata
Source: Prairie Habitat Joint Venture: Implementation Plan 2007-2012 (2009)

Positive mathematical programming (PMP) is used to calibrate a land-use model to observed land uses in the PPR study region. The calibrated model is then used to examine the impact of various policies related to climate change. PMP was originally developed by Howitt (1995), who applied it to a simple example involving crop yields. He added constraints to a linear programming model to insure that modeled outcomes duplicated actual outcomes, and then employed the shadow values from these 'calibration' constraints to estimate a nonlinear objective function, which replaced the linear objective function. Solving the model with the revised objective and original linear constraints resulted in outcomes that exactly matched observed values. Howitt (2006) also extended the approach to the dual problem, which enabled the calibration of nonlinear cost functions.

Studies regularly use PMP to estimate the effect of environmental policies on land use. Agriculture and Agri-Food Canada uses PMP to calibrate the Canadian Regional Agriculture Model, which includes environmental components to estimate the effect of different policies on land use.[1] PMP is also used in California's Central Valley Production Model, which estimates the impact of the Central Valley Project Improvement Act on agriculture (Hatchett et al. 1997). Many studies use PMP to examine the impact of environmental policies in the European Union on the agricultural sector (e.g., Gohin 2000; de Frahan 2007). Yet, to our knowledge, no studies use PMP to model land use change in the context of wetlands management.

[1] Model details can be found at (accessed March 15, 2011) http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5351.php.

There are several studies, however, that employ an alternative approach to investigate the optimal management of wetlands. Brown and Hammack (1973), Hammack and Brown (1974), and Brown et al. (1976) were the first to use mathematical bioeconomic models to address wetlands conservation. They specified a discrete bioeconomic 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 et al (2011) included the ecosystem amenity value of wetlands and viewing value of waterfowl. 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 analysis 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 with global warming the most productive waterfowl habitat will be confined to the northern and eastern parts of the PPR. None of these studies used constrained optimization. An exception is Withey and van Kooten (2011), who extended van Kooten et al.'s (2011) model to consider the impact of climate change on wetlands management. They find that climate change could decrease optimal wetlands retention by as much as 38 percent.

In the current application, we employ a multi-regional land use model that allows us to explicitly model the tradeoffs between agricultural production and wetlands management. We calibrate separate models for each of strata 26-40 used by the U.S. Fish and Wildlife Service Population Survey (Figure 1) using the PMP methodology. In doing so, we employ 2006 as a 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. Lacking data on net returns to wetlands, the model relies on private returns (wetlands represent a cost) plus public returns (positive social benefits). In addition to base-case results, we estimate how expected climate change induced changes in crop yields will impact land use. We also estimate how higher returns to canola will impact land use; higher returns represent a policy-induced increase in the demand for biofuels.

As an indicator of the potential severity of climate change, our results predict that the wetlands area to be retained in the study region could potentially be reduced by as much as 50% from 2006, even if social benefits of wetlands are considered. If the social benefits of wetlands are ignored, the decrease in wetlands could be significantly higher. Direct climate effects will have a greater impact than incentives to increase biofuel production. Not surprisingly, results are heterogeneous across regions within the PPR, with differences quite pronounced in some instances.

The paper proceeds as follows. In the next section, we develop the positive mathematical programming model, followed, in section 3, with a discussion of the data used to solve the base case, 15-region model. In section 4 we discuss climate change scenarios and present the results of the analysis in section 5. Implications are discussed in section 6.

2. Analytic Model: Positive Mathematical Programming

Positive Mathematical Programming (PMP) uses the notion that any (linear) calibration constraint can be represented in the objective function as a nonlinear cost or yield function (Howitt 1995). Thus, rather than adding arbitrary calibration constraints to a linear program (LP) to replicate observed land use, the PMP method uses 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 that is derived using PMP takes into account the farmers' reasons for planting multiple crops, such as risk or unobserved costs; its parameters represent those that best describe how the farmer chose the observed allocation of land among crops. PMP has a theoretically sound calibration mechanism, allowing for accurate scenario analysis.

The PMP method is implemented in three stages. The first involves maximizing net returns to land uses (using an LP), subject to resource and calibration constraints:

$$\text{Max} \quad \sum (p_i y_i - c_i) x_i \tag{1}$$

$$\text{s.t.} \quad \sum a_{ji} x_i \le \overline{R}_j, \forall j \tag{2}$$

$$x_i \le x_i^0 + \varepsilon_i \tag{3}$$

where p_i, y_i and c_i are the prices, yields and average costs for each of land uses i; the allocation of land to activity i is denoted x_i; a_{ji} are the technical coefficients of production (the amount of resource j required per unit of x_i); and $\overline{R}_j$ is the total amount of resource j that is available. Much like the Canadian Regional Agriculture Model (CRAM), we consider only the land resource so that $a_{\text{i,land}} = 1$ for all i.[2] Constraints (3) constitute the calibration constraints needed to implement PMP, with x_i^0 are the observed areas in each land use and ε_i are perturbation terms that are chosen to be a very small positive numbers. The model is solved for each of the 15 strata for nine available land activities.

Dual values from the LP described by (1), (2) and (3) are then used in the second stage of the PMP calibration to estimate the parameters of a nonlinear yield function for each crop in each region. Assuming a quadratic yield function, $y_i = (\beta_i - \gamma_i x_i)$, Howitt (1995) shows

[2] Unlike the current application, the CRAM model considers a water resource constraint in addition to land constraints.

that the dual values on the calibration constraints, λ_{2i} in equation (3), are equal to the difference between the value of the average and marginal products of land, VAP and VMP, respectively. Thus, γ_i and β_i are derived as follows:

$$\lambda_{2i} = \text{VAP}_i - \text{VMP}_i = p_i(\beta_i - \gamma_i x_i) - p_i(\beta_i - 2\gamma_i x_i) = p_i \gamma_i x_i \quad (4)$$

$$\gamma_i = \frac{\lambda_{2i}}{p_i x_i} \quad (5)$$

$$\beta_i = y_i + \gamma_i x_i \quad (6)$$

Given the dual values for each calibrated land use (λ_{2i}), as well as data on p, y and x, one can calibrate nonlinear yield functions that represent the decisions of landowners in a given region.

The perturbation coefficient on the right hand side of equation (3) forces the LP to produce dual values that are then used to parameterize the yield function. 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, where the calibration constraint does not bind and the activity is constrained only by the land use equation (2).[3] When λ_{2i} 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 γ_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. This assumed yield reduction causes a 20% reduction in the opportunity cost of land (λ_1) in producing the marginal crop. In order 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.[4] This new value of λ_2 for the marginal crop, $\overline{\lambda}_{2,marginal}$, can be used to calculate the non linear yield function for the marginal activity. All other λ_{2i} values must be adjusted by $\overline{\lambda}_{2,marginal}$.

In the third step, the PMP problem becomes:

$$\text{Max} \qquad \sum (p_i(\beta_i - \gamma_i x_i) - c_i) x_i \quad (7)$$

[3] Recall that, in the current application, we have only one equation in (2), namely, a land constraint, so $a_{i,land} = 1$, and there is only one shadow price, λ_1.

[4] See Howitt 1995, p337 for more detail and an example.

s.t. $$\sum a_i x_i \leq \overline{R} \qquad (8)$$

This model uses the calibrated yield function from the second stage to represent the landowners' decisions. Using only the resource constraint (8), the solution replicates the observed allocation for a base year. For different scenarios (discussed in section 4), only the parameters in (7) need to be adjusted.

3. Data for the Base Case Model

To solve the land use model of the previous section, observed acreage (*x*), yield (*y*), price (*p*) and variable cost (*c*) data are required for each stratum and each land use. We solve the model for a base year of 2006, and obtain data for each variable for that year. We first discuss data sources for crops (spring wheat, winter wheat, barley, oats, dry field peas, canola and hay) and then discuss how wetlands and pasture are treated in this model.

Crops

All observed acreage data (excluding wetlands) come from the 2006 Census of Agriculture (Statistics Canada, 2007). The data from each of the Census Consolidated Sub-Division (CCS) in the Census of Agriculture are overlapped with stratum-level waterfowl population and wetland data from the U.S. Fish and Wildlife Service (2010). If 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.[5] For strata 30-35, the Government of Saskatchewan provides yields by crop for each rural municipality (RM).[6] In this study, several RM are chosen within each stratum to obtain the yield data per stratum. For strata 36-40 in Manitoba, yield data are available by crop and by risk area, which we match to each stratum.[7]

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 come from the same source as the yield data. For strata 30-35, operating costs come from

---

[5] http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/econ10237 (accessed March 15, 2011).

[6] http://www.agriculture.gov.sk.ca/rmyields (accessed March 15, 2011).

[7] http://www.gov.mb.ca/agriculture/crops/cropproduction/gaa01d27.html (accessed March 15, 2011).

crop planning guides published by region by the Government of Saskatchewan.[8] 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.[9]

Pasture and Wetlands

Wetlands and pasture land must be treated differently than land in crops, since no direct revenues accrue to wetlands or pasture. There is information on observed areas in each activity: land in pasture comes 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 for 2010. Ponds counts are converted to acres using an average pond size of 0.85 acres (van Kooten et al. 2011). However, there are no value data for prices, yields or variable costs; to include these land uses in the model, we specify net returns by region for these activities.

First, from a land use standpoint, pasture provides benefits to farmers as an input into livestock production. Since we do not include livestock in this model, we simply assume the value to farmers of having pasture equals $20 per acre, regardless of region, which is less than the net revenue to cropland. In all strata, the price of a unit of forage is assumed to be $4, while yield is 5 units per acre and variable costs are zero.

Second, as discussed in the introduction, wetlands have been drained because they represent a cost to private landowners, despite the fact that wetlands provide considerable social benefit. Meta analyses by Woodword and Wui (2001) and Brander et al. (2006) estimate the benefits of the various ecological functions provided by wetlands. These functions are summarized in Table 1.

Table 1: Ecological Values of Wetlands

Ecological function	Economic goods and services
Flood and flow control	Flood protection
Storm buffering	Storm protection
Sediment retention	Storm protection
Groundwater recharge	Water supply
Water quality maintenance	Improved water quality
Habitat for plants and animals	Commercial and recreational fishing/hunting
Biological diversity	Appreciation of species existence
Micro-climate stabilization	Climate stabilization
Carbon sequestration	Reduced global warming
Natural environment	Amenity value/recreation

Source: Brander et al. (2006, p.226)

From the literature, the social benefits of wetlands can range from $10 per acre (Cortus et

[8] http://www.agriculture.gov.sk.ca/crop-planning-guides (accessed March 15, 2011).
[9] http://www.gov.mb.ca/agriculture/financial/farm2005/cac40s01.html (accessed March 15, 2011).

al. 2010) to $150 per acre (Brander et al. 2006). It is these benefits that the authority (social planner) needs to consider, because loss of wetlands imposes a cost on society as ecological values described in Table 1 are forgone.

In this study, 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 social planners' perspective, where wetlands are determined to 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 net cost due to foregone agricultural production. The value of wetlands to both the private landowner and social planner are 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 cost of wetlands restoration. It is assumed that the landowner incurs an annual marginal cost of $5 per acre for providing wetlands (see Cotus et al. 2011; van Kooten et al. 2011).

Private landowners receive no benefit from retaining wetlands. From society's perspective, however, wetlands provide benefits related to water filtration and flood control, wildlife habitat, amenity (viewing) values, greenhouse gas storage, production of waterfowl, and so on (see Table 1). Historical 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. Based on bioeconomic models, we assume a shadow price for ducks of $7, so that the value of wetlands in producing ducks is $5.67-42.98 per acre.[10]

The shadow value of wetlands varies considerably across the PPR, depending on the productivity of wetlands, but this captures only the benefits of duck production for the purpose of hunting. To address the ecosystem service and other amenity values of wetlands, we assume a constant value of $35 per acre plus a value that takes into account the quality of the wetlands, as determined by the productivity of wetlands in duck production. We put less weight on the productivity of wetlands in duck production, since there is such variation in this estimate across regions. Thus, the value of wetlands area is given by the following function:

$$\text{Net Revenue}_{\text{wetlands}} = \$35/\text{ac} + 0.25 \times \text{ducks/ac} \times \$7/\text{duck} \tag{9}$$

Thus, social returns to (benefits of) wetlands vary from $36.40 to $46.9 per acre. This range of values is consistent with those found in the literature. Further, this metric captures the total benefit of wetlands, with benefits varying by region based on the

[10] Hammack and Brown (1973) estimated a value of $3 per duck, while the estimate from van Kooten et al. (2010), which includes amenity values of ducks, is around $10 per duck.

productivity of wetlands in producing waterfowl.

4. Climate Change

Climate Scenarios

This section outlines three climate scenarios that are used to determine the impact of climate change on wetlands in the PMP model. First, direct climate change impacts on land use in the study region are modeled via the impact of climate on crop yields. By changing yields, one changes the value of crops relative to wetlands and thereby the amount of land optimally allocated to wetlands. A regression model used to estimate the impact of annual precipitation and average maximum temperature on average crop yields for each crop in each stratum is as follows:

$$y_{ir}= \beta_0 + \beta_1 P_r + \beta_2 T_r + \varepsilon_{ir}, \tag{10}$$

where y_{ir} is observed average yield for crop i in region r; P_r and T_r are the precipitation and temperature, respectively, affecting region r; β's are parameters to be estimated; and ε is the error term. Given the estimated β's and an expected future climate scenario, one can estimate the change in yields from historical averages brought about by the changed climate. For scenario #1 estimates of the impact on yields are based on an increase in temperature of 3^{o}C and a decrease in precipitation of 10% (see Larson 1995; Sorenson et al. 1998; Johnson et al. 2005; Withey and van Kooten 2011).

Second, although climate change affects crop yields and thereby wetlands, a warmer and drier climate also directly leads to a loss of wetlands. A loss of wetlands changes the returns to cropping activities relative to wetland values; in areas where wetlands are lost, the opportunity cost of converted now-dry wetland to crops is reduced. Thus, looking only at changes in crop yields will underestimate the effect of climate on wetlands, and it is important to consider the direct effect of climate on wetlands. This is done by estimating equation (10) for wetlands as well, with the left-hand-side variable now measured in terms of area and not as a yield. Therefore, scenario #2 examines the impact of climate change on wetlands acreage in addition to estimating the effect of climate on crop yields. This is done for each region of the PPR as climate change affects wetlands and crop yields differently in each region via equation (10).

Finally, scenario #3 examines the impact of policies to mitigate climate change, namely, the Canadian government's Renewable Fuel Standard (RFS) that was implemented in May 2008. This policy requires two percent renewable content in diesel fuel by 2010 and 5 percent 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 dollars per metric ton for the 2-percent blend and by $200 per ton for the 5-

percent blend. For the PMP model, the RFS policy thus represents a 7% increase in the price of canola for the 2-percent blend and a 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 10%. Scenario #3 considers the direct climate effects on crops and wetlands, as well as the increased price of canola.

Predicted Impact of Climate Change on Crop Yields and Wetlands Area

To estimate the impact of climate change on land use, data are required to estimate regression equation (10) for each crop and each stratum. Historic yield data are available for most crops by region for the period 1955 to 2008. For Alberta and Manitoba, these data were obtained through correspondence with relevant individuals in the respective agricultural ministries of these provinces.[11] In Saskatchewan, historic yield data by crop are available from their website (as indicated in section 3 above). Precipitation and temperature data come from Environment Canada's historical weather information, found in the National Climate Data and Information Archive.[12] Average annual maximum temperature and total precipitation are taken from a single weather station selected in each of the strata.

The regression model (10) is estimated for each of the land use activities and wetlands using ordinary least squares with results provided in Table A1 in the Appendix. For the most part, temperature and precipitation have a positive marginal impact on yields, with such effects significant at the 5% or 10% level. If a coefficient had a sign that was unexpected, was insignificant or reduced the adjusted R^2, it was not included in the specification (as indicted by an entry of 'na' in the table). Based on the statistical significance of the coefficients, the regression model provided a better fit to the data in Alberta and Saskatchewan than in Manitoba.[13] The same specification was employed for all strata for consistency.

Assuming that landowners make no adjustments to input use (such as fertilizer) as a result of climate change, the projected changes in crop yields and wetlands area relative to historic values are provided in Table 2. For hay land and peas, for which there were no data, estimated effects are conservatively assumed based on the results for other crops. For crops, values in Table 2 represent a decrease from historic levels in bushels per acre, whereas wetlands represent a decrease from historic levels in acres.

---

[11] For Alberta, the most recent data are found at (accessed on March 15, 2011): http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12891.

[12] At http://www.climate.weatheroffice.gc.ca/Welcome_e.html (accessed on March 15, 2011).

[13] The reader will need to match strata and provinces using Figure 1.

Table 2: Change in Crop Yields and Wetlands Area due to 3°C Higher Temperatures and 10% Lower Precipitation, % Change by Stratum[a]

	Wheat	Barley	Oats	Canola	Dry Field Peas	Hay land	Wetlands
26	14.00	19.00	13.00	39.8		10.00	-25.0
27	6.22	8.80	7.55	20.23			-29.35
28	17.40	16.58	13.46	30.24		15.79	-31.09
29	16.56	14.92	9.22	32.2		16.22	-20.88
30	-2.08	2.74	-1.05	5.42		-19.02	-54.03
31	3.85	10.31	7.16	16.26	0.88		-43.24
32	-3.56	-2.92	-9.85	3.71	0.15		-50.8
33	11.84	12.83	16.40	15.05	34.76		-28.85
34	6.69	12.02	6.06	25.18	5.10		-51.34
35	-2.06	2.35	-2.26	5.54			-43.80
36	-5.60	0.61	-1.37	7.24			-7.32
37	13.42	21.98	14.98	3.48			-38.92
38	9.49	16.64	17.88	26.68			-18.89
39	-2.67	-4.54	-4.46	1.26			-35.00
40	-1.36	5.28	3.27	15.64			-33.93

[a] Projections based on the estimated coefficients in Appendix Table A1.

For most crops in Table 2, the climate change scenario used in this paper will lead to an increase in crop yields due to warmer temperatures. Overall, the positive impact of climate on yields is highest in canola and lowest in wheat. Not surprisingly, impacts vary substantially by region and, in a few cases, the decline in precipitation outweighs the temperature effect, leading to lower crop yields. In Alberta (strata 26-29), climate change is projected to have a high positive impact on all crop yields in all strata. For several strata in Saskatchewan (strata 30-35) and Manitoba (strata 36-40), the increase in crop yields will be minimal or there may even be a decline.

Wetlands will be dramatically reduced due to warmer, drier conditions; the average reduction across regions is 29.3 percent. The reduction in wetlands in Alberta is about average, in Saskatchewan above average, and in Manitoba below average.

5. Results

Results of PMP model (base case) and Climate Change Effects on Land Use

The three-stage PMP model was solved in GAMS using the CPLEX and CONOPT3 solvers. Appendix Table A2 provides parameter values for the non linear yield functions that were estimated and used to solve the PMP model, while Table 3 presents the PMP modeling results. In the first two rows of Table 3, the observed (2006) and PMP model, base-case land uses are presented. A comparison indicates that the model replicates the observed land uses almost exactly, suggesting that the model is suitable for policy analysis.

The bottom four rows of Table 3 provide the optimal land use allocations under each of the three climate scenarios identified in section 4. For each scenario, we include the social value of wetlands, but, in the final row of the table, we ignore externality benefits of conserving wetlands and consider the case where wetlands have value only to landowners – only private returns are considered so wetlands retention represents a cost. This allows us to compare how climate change will impact wetlands management if they are privately managed versus management by a social planner.

To estimate the climate impact for scenario #1, we adjusted the yield data to account for the climate effects presented in Table 2. Then, to estimate the impact of scenario #2, we added as an adjustment the calibrated marginal yield parameter from Table A2 for wetlands. The marginal yield parameter was adjusted because there is no 'yield' from wetlands that is impacted by climate. Finally, to estimate the impact under scenario #3, we added to the previous changes the increase in the price of canola in all regions.

Table 3: Land Uses: Observed (2006), Calibrated PMP Model, and Climate Change Scenarios ('000s ac)

Scenarios[a]	Spring wheat	Barley	Oats	Winter wheat	Canola	Dry peas	Wetland area	Hay land	Pasture
Observed	14626.1	7799.6	4020.4	406.7	11257.8	2992.9	3782.1	10551.4	9059.0
PMP Base	14621.1	7806.8	4019.1	409.2	11269.6	2975.3	3785.8	10562.6	9032.9
#1	13988.9	8429.0	4087.8	430.5	17591.9	3207.8	3285.7	9036.5	4433.9
#2	14563.1	8544.9	4111.5	433.4	17680.0	3311.2	1952.0	9132.4	4735.9
#3 (social)	13823.2	7967.0	4058.2	427.3	20231.6	3139.0	1877.3	8646.5	4321.9
#3 (private)	13959.4	8093.6	4083.4	430.8	20275.3	3298.8	831.5	8788.9	4730.2

[a] Scenario #1 refers to change in crop yields due to increasing temperature by 3^{o}C and decreasing precipitation by 10%; scenario #2 is the same as #1 but adds the projected change in wetlands under the same climate scenario; and scenario #3 adds to #2 an increase in the price of canola of 10%. Under scenario #3, two scenarios are considered depending on whether wetlands are valued at their social or only private net benefit.

In addition to the results provided in Table 3, shadow values of the land resource constraint (λ_1) vary by region – from \$5 per acre in strata 26-27 to \$19 per acre in several strata in southern Alberta and Manitoba. Finally, the model determines which crops are marginal or less profitable. As noted earlier, these crops have a zero dual value for the calibration constraint, λ_2. Wheat is a marginal crop in several strata in Saskatchewan; oats are marginal in two strata in Saskatchewan; peas are a marginal crop in six strata, two in each province; and pasture is a marginal crop in seven strata across the three provinces.

Several trends are discernable from the climate change effects in Table 3. First, in terms of cropland, the changes modeled under scenario #1 suggest that climate change has the most pronounced positive effect on canola and barley plantings. This is not surprising given the yield changes expected as a result of climate change (see Table 2). Compared to canola and barley, optimal plantings of most other field crops increase marginally, while those of spring wheat decline by between 0.5 and 5.5 percent, depending on the scenario. In contrast plantings of winter wheat are projected to increase (but overall acreage will remain small), thereby benefitting waterfowl that nest in winter wheat. As noted, canola planting might increase by more than 50% as a result of climate change, but plantings are boosted by another 15% or so when biofuel policies increase the price of canola.

Wetlands area is projected to decrease by about 13% due to the increased value of crops relative to wetlands (scenario #1), but, when the direct effect of climate change on wetlands is factored in (scenario #2), wetlands are reduced by an additional 35%, or by almost one-half of today's area. The impact of an increase in the price of canola on wetlands (scenario #3) is minimal.

Finally, if the social value of wetlands is used as the basis for scenario #3, the reduction of wetlands is roughly projected to be 50% from current levels. This is consistent with results by Withey and van Kooten (2011b), who estimated the effect of climate change and biofuel policies on wetlands using an optimal control approach that took account of the social benefits of wetlands. However, if social values are ignored by a private landowner, wetlands area falls by about 80% from that observed today. Meanwhile, the amount of land in pasture is projected to fall by about one-half in all three scenarios, because its value falls significantly compared to that of other land uses.

Regional Climate Effects

The percentage changes in land allocation are provided in Table 4 for each of the fifteen strata, but only for scenario #3, where the private landowner is provided incentives to take into account the social values of wetlands. A summary of the reduction in wetlands under this same scenario is provided in Table 5. Results confirm those of Table 3. The largest increase in land use triggered by predicted global warming is in canola, while the largest decreases are in pasture and wetlands, both of which are suitable waterfowl habitat. Other land uses are expected to experience marginal increases or declines. We focus the rest of this discussion on how wetlands loss compares across strata.

Table 4: Projected Change in Land Uses from Base Case, by Stratum, Scenario #3 including Social Benefits of Wetlands (%)

Strata	Spring wheat	Barley	Oats	Winter wheat	Canola	Dry field peas	Wetlands	Hay land	Pasture
26	-21.1	-36.1	-6.5	-20.5	298.1	-100.0	-67.6	-84.7	-100.0
27	-11.1	-23.4	-0.4	-13.0	197.2	-100.0	-45.4	-11.3	-54.4
28	15.7	29.5	14.9	16.9	50.5	32.2	-47.4	2.7	-100.0
29	20.9	34.0	12.4	22.6	56.8	40.2	-31.5	12.8	-88.2
30	-6.2	10.9	-1.1	-4.0	19.0	8.4	-53.1	-26.7	11.1
31	-0.2	17.9	8.5	-2.2	38.8	-50.8	-51.0	-4.1	-81.0
32	-10.4	3.6	-11.6	-2.2	34.2	14.1	-45.9	0.9	16.2
33	7.9	20.0	12.7	23.4	26.1	43.8	-35.0	-11.5	-18.3
34	1.1	16.4	3.7	3.4	56.8	-30.4	-59.2	-3.3	-37.8
35	-7.3	-0.6	-6.4	-10.4	75.4	-76.3	-46.0	-5.0	-7.2
36	-12.4	-0.2	-2.1	-36.1	17.9	18.2	-6.9	-9.1	-1.5
37	27.9	52.2	13.4	23.1	12.3	36.6	-47.2	10.5	-70.9
38	0.1	10.4	9.3	0.1	34.1	-9.9	-66.4	-23.4	-100.0
39	-32.9	-50.7	-4.6	-14.1	27.4	714.5	-33.7	-2.1	3.2
40	-10.1	3.1	0.8	-8.5	29.8	195.9	-41.5	-9.7	-28.1
Total	-5.5	2.1	1.0	4.4	79.5	5.5	-50.4	-18.1	-52.2

Table 5: Original Level of Wetlands and Projected Wetlands under Scenario #3 with Social Benefits of Wetlands Included, by Stratum ('000s ac)

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	3786
Scenario #3	149	76	76	71	182	261	293	48	227	119	61	118	17	105	75	1877

The change in wetlands across regions in the PPR ranges from a loss of between seven and nearly 70 percent (Table 4), or 4000 to 330,000 acres (Table 5). Unsurprisingly, the effect of climate change and climate change policies on wetlands is not homogenous across regions, because climate and soil characteristics (which impact crop yields and crop revenue) differ dramatically across the study region. In Table 4, the largest proportional declines in wetlands are in strata 26, 38, 34, 30 and 31, while the largest decreases in wetlands area (Table 5) are in strata 34, 26, 31, 32 and 30. Thus, wetlands loss is greatest in northern Alberta (stratum 26) and Saskatchewan (strata 30, 31, 32 and 34).

Recall that, in the land-use model, changes in wetlands in each stratum are driven primarily by the actual climate effect on wetlands area as determined from the relation in Appendix Table A1. 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 caused by biofuel policies to address climate change. Overall, therefore, there is a direct climate impact on wetlands and an indirect impact resulting from increases 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 4 and 5. In doing so, it is helpful to consult Figure 1.

The largest actual reduction in wetlands area is projected to occur in Saskatchewan (strata 30-35). This is due in part to the fact that the largest areas of wetlands are found in Saskatchewan; however, some of the largest proportional declines are also projected to occur in Saskatchewan, particularly in strata 30, 31 and 34. The declines in wetlands in these strata are driven by severe climate impacts (Table 5), while increased crop yields in strata 31 and 34 also reduce the relative value of wetlands. Overall, however, wetland loss in Saskatchewan is only slight greater than the PPR average of 50%.

Wetlands loss in Alberta (strata 26-39) is projected to total 56%, which is the largest proportional loss of wetlands in the three provinces. The reason relates primarily to strata 26, because of large plantings of canola, which is the dominant crop in this area. Canola plantings in strata 26 are projected to increase significantly under climate change, and especially if governments aggressively pursue biofuel policies. Climate effects on wetlands in the other three strata are below average, but crop yields are significantly increased due to a warmer climate, implying that cropping becomes a more valuable activity compared to retaining land in wetlands. The significant loss of wetlands in Alberta is consistent with earlier projections using an optimal-control, bioeconomic model (see Withey and van Kooten 2011b).

Finally, the overall projected reduction in wetlands in Manitoba is smaller than that in the other provinces. While the proportional loss of wetlands in stratum 38 could be large, the associated actual loss in area is quite small. Because average climate change impacts on both wetlands and crop yields are smaller than for the other provinces, the overall wetlands loss in Manitoba is also well below the PPR average, but still significant at 40 percent.

6. Discussion

In this study, we used 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. We built a model consisting of 15 regions and nine land uses per region, and calibrated it almost exactly to observed land use in the PPR. Using the model, we project that climate change will reduce wetlands by at least 50% from 2006 (observed) levels. Our results indicate that, if social benefits of wetlands are ignored by landowners and policymakers, then the effects of climate on wetlands will be severe, with as much as 78% of current wetlands in the PPR potentially being lost.

The impact of climate change on wetlands will not be homogenous across regions, however, as the largest wetlands losses projected to occur in Alberta (in percentage terms) and Saskatchewan (in absolute terms). With drier conditions, it will be optimal to have more wetlands in Manitoba than Alberta, which has not been the case historically. In our models, the warming-induced shift in wetlands in Canada's pothole region is from the west to the east. 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 southeastern Saskatchewan to the northern and eastern fringes if climate change comes about as predicted.

The current research provides a framework for understanding how climate change will affect land use in the PPR, because it analyzes the tradeoffs between all major land uses. It also provides guidance for policymakers. First, whether or not decision makers consider the social benefits of wetlands will have serious implications for wetlands management. Policies need to be developed that internalize the external benefit from wetlands by providing payments to landowners for retaining wetlands. Second, since global warming could severely reduce wetlands, policymakers need to implement plans in timely fashion to minimize losses. Based on this analysis, it is clear that the largest decreases in wetlands will be in Alberta and Saskatchewan, while the smallest are in Manitoba. Yet, it will still be optimal to have more wetlands in Saskatchewan than Alberta or Manitoba, despite potentially significant losses in the former. Given that climate change will have the greatest impact on wetlands in 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 west to east, it may be necessary to target wetlands protection in Manitoba as well. However, it remains an open question as to whether Manitoba can make up for lost wetlands in Saskatchewan.

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

References

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

Brown, G.M., J. Hammack and M.F. Tillman, 1976. Mallard Population Dynamics and Management Models, *Journal of Wildlife Management* 40(3): 542-555.

Brown, G.M. and J. Hammack, 1973. Dynamic Economic Management of Migratory Waterfowl, *Review of Economics and Statistics* 55(1): 73-82.

Cortus, G., S. Jeffrey, J. Untershultz, and P. Boxall, 2011. The Economics of Wetland Drainage and Retention in Saskatchewan, *Canadian Journal of Agricultural Economics*, 59(1): 109-126.

de Frahan, B.H., J. Buysse, P. Polome, B. Fernagut, O. Harmignie, L. Lauwers, G. Van Huylenbroeck and J. Van Meensel, 2007. Positive Mathematical Programming for Agricultural and Environmental Policy Analysis: Review and Practice. In *Handbook of Operations Research in Natural Resources* (pp.129-154). Eds: Weintraub, A., C. Romero, T. Bjorndal and R. Epstein. New York: Springer.

Gohin, A., 2000. Positive Mathematical Programming and Maximum Entropy: Economic tools for applied production analysis. INRA Seminar on Production Economics November 2000, Paris.

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

Hatchett, S., R.Mann and B. Zhang, 1997. Analysis of Agricultural Economics for the Central Valley Project Improvement Act Programmatic Environmental Impact Statement. Presented at Western Agricultural Economics Association 1997 Annual Meeting. Reno/Sparks, Nevada

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

Howitt, R.E., 2006. *Agricultural and Environmental Policy Models: Calibration, Estimation and Optimization*. Available at (accessed June 1, 2011) http://agecon.ucdavis.edu/people/faculty/richard-howitt/docs/c1.pdf

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

Johnson, F.A., C.T. Moore, W.L. Kendall, J.A. Dubovsky, D.F. Caithamer, J.R. Kelley, Jr. and B.K. Williams, 1997. Uncertainty and the Management of Mallard Harvests, *Journal of Wildlife Management* 61(1): 202-216.

Johnson, W.C., B.V. Millett, T. Gilmanov, R.A. Voldseth, G.R Guntenspergen and D.E. Naugic, 2005. Vulnerability of northern prairie wetlands to climate change, *BioScience* 55: 863-872.

Johnson, W.C., B. Werner, G.R. Gunmtenspergen, R.A. Voldseth, B. Millet, D.E. Naugle, M. Tulbure, R. Carroll, J. Tracy and C. Olawsky, 2010. Prairie wetland complexes as landscape functional units in a changing climate, *BioScience* 60(2): 128-140.

Larson, D., 1995. Effects of climate on numbers of northern prairie wetlands, *Climatic Change* 30: 169–180.

Mitsch, W.J. and J.G. Gosselink, 2007. *Wetlands*, fourth edition. John Wiley and Sons, Inc.: Hoboken, New Jersey.

Mussell, A. (2010). Effect of Mandated Biodiesel Blend on Canadian Canola. George Morris Centre Policy Analysis. Available at (accessed March 15, 2011): http://www.georgemorris.org/GMC/Publications/PolicyAnalysis.aspx#

PHJV Waterfowl Working Group (2009). Prairie Habitat Joint Venture: Implementation Plan 2007-2012. Available at (accessed February 1, 2011): http://www.phjv.ca/pdf/PHJV%20Implementation%20Plan%20090506-lowres.pdf

Sorenson, L.G., R. Goldberg and M.G. Anderson, 1998. Potential effects of global warming on waterfowl populations breeding in the northern Great Plains, *Climatic Change* 40: 343–369.

Statistics Canada, 2007. *2006 Census of Agriculture*. Statistics Canada: Ottawa, Ontario. Available at http://www.statcan.gc.ca/ca-ra2006/index-eng.htm (accessed June 1, 2011).

U.S Fish and Wildlife Service, 2010. Waterfowl Breeding Population and Habitat Survey. Division of Migratory Bird Management. Available at http://migbirdapps.fws.gov and http://www.fws.gov/migratorybirds (accessed January 19, 2011).

van Kooten, G.C., P. Withey and L. Wong, 2011. Bioeconomic Modeling of Wetlands and Waterfowl in Western Canada: Accounting for Amenity Values, *Canadian Journal of Agricultural Economics* 59(2): 167-183.

Withey, P. and G.C. van Kooten, 2011. The Effect of Climate Change on Optimal Wetlands and Waterfowl Management, *Ecological Economics* 70: 798-905.

Withey, P. and G.C. van Kooten, 2011b. The effect of climate change on wetlands: incorporating cropping decisions into a bioeconomic model. University of Victoria Working paper.

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

Table A1: Estimated Parameter Estimates for Climate Equation (10)

Stratum	Parameter	Wheat	Barley	Oats	Canola	Hay	Peas	Wetlands
26	β_0	-1.7	-10.9	0.31	-9.62			
	β_1	2.22**	3.88**	3.59**	2.98**			
	β_2	0.042**	0.059**	0.067**	0.012			
27	β_0	-3.23	-2.58	-0.32	-8.71			0.19**
	β_1	1.27	2.1*	2.31*	1.87**			-0.009
	β_2	0.049**	0.063**	0.073**	0.029**			3.43E-0.5
28	β_0	-9.06	-10.08	-11.05	-20.5*	-0.25		0.267**
	β_1	2.12**	3.19**	3.18**	2.77**	0.118*		-0.001**
	β_2	0.04**	0.055**	0.07**	0.03**	0.002*		-0.0002**
29	β_0	-18.8	-19.3	-17.1	-30.5**	-0.88		0.157**
	β_1	2.29**	3.21**	2.78**	3.06**	0.13**		-0.006*
	β_2	0.037*	0.05**	0.06**	0.03**	0.001**		na
30	β_0	2.57	-0.49	-1.76	5.87	1.08		0.23**
	β_1	0.51	1.42	1.27	0.75**	na		-0.033
	β_2	0.057**	0.08**	0.12**	0.028	0.0019		0.0007
31	β_0	11.25	5.42	4.8	4.46		7.97	0.52**
	β_1	0.76	2.12**	2.33**	1.43**		0.63	-0.052**
	β_2	0.029**	0.05*	0.078*	0.018**		0.042**	0.00055**
32	β_0	13.66	22.4	29.29	6.63		19.43	1.16
	β_1	na	0.01	na	0.48		0.64	-0.077**
	β_2	0.028**	0.04**	0.054**	0.02**		0.005	na
33	β_0	-8.77	-16.03	-33.3*	-2		-32.4	0.18
	β_1	1.47**	2.41**	3.8**	1.21**		3.67**	-0.009*
	β_2	0.05**	0.08**	0.12**	0.02**		0.086**	na
34	β_0	10.83*	8.07	12.33	7.41		13.58	0.92*
	β_1	0.92	2.25*	1.92	1.74**		0.75	-0.07*
	β_2	0.02**	0.04**	0.055**	0.001		0.02	na
35	β_0	12.7	12.59	18.84	4.34			0.65**
	β_1	0.14	0.81	0.36	0.62			-0.04**
	β_2	0.02**	0.03**	0.05**	0.02**			na
36	β_0	14.89*	23.5	25.45**	11.95			0.05
	β_1	na	0.06	0.27	0.36*			-0.0008
	β_2	0.034**	0.005	0.02	na			2.86E-0.5
37	β_0	18.59**	18.77	33.88*	6.7			0.39**
	β_1	1.4*	3.26**	2.79*	0.18			-0.02**
	β_2	0.002	na	na	0.004			0.0001
38	β_0	10.36	8.24	-9.15**	-7.94			0.07**
	β_1	1.32	3.15*	4.36**	2.47**			-0.0029
	β_2	0.02*	0.027	0.057**	0.021*			na

39	β_0	22.36	21.82*	28.17**	5.96			0.28
	β_1	na	na	na	0.35			-0.017**
	β_2	0.019**	0.039**	0.05**	0.019**			na
40	β_0	26.57	22.63*	22.84	2.81			0.32**
	β_1	0.01	1.27	1.37	1.38*			-0.02**
	β_2	0.01	0.03*	0.05**	0.017**			na

*indicates significance at the 0.10 level of significance; ** indicates significance at 0.05 level of significance

Table A2: Nonlinear Yield Parameters

Strata	Wheat	Barley	Oats	Canola	Hay	Peas	Wetlands	Hay	Pasture
				Maximum yield, $\beta_i = y_i + \gamma_i x_i$					
26	60.05	73.35	112.42	60.30	51.03	38.75	11.31	80.62	8.75
27	52.33	62.92	89.95	50.52	44.03	38.40	11.39	101.62	8.75
28	63.76	81.19	89.51	62.76	56.55	45.40	10.17	112.59	5.95
29	63.76	79.97	86.87	62.76	57.25	44.70	9.87	104.89	5.95
30	41.69	65.65	94.85	38.50	43.41	48.37	9.31	80.39	5.95
31	43.97	69.50	94.64	38.86	42.61	33.52	9.07	96.49	5.95
32	28.19	47.32	57.60	53.67	30.92	34.85	11.93	98.28	8.35
33	34.08	54.65	92.79	44.45	21.75	33.00	11.79	102.59	9.75
34	34.69	67.20	73.93	51.25	41.89	32.70	9.30	104.75	7.95
35	37.12	54.57	62.72	50.62	25.19	28.16	10.79	103.99	9.75
36	66.34	83.63	132.47	45.06	62.81	39.48	7.51	89.49	5.95
37	68.46	96.81	145.62	70.46	54.96	50.32	8.01	102.79	5.95
38	81.60	117.23	191.89	83.60	76.15	57.05	8.61	100.69	5.95
39	41.27	53.62	91.28	43.27	37.56	40.58	10.87	100.21	8.75
40	61.19	96.24	180.23	63.19	61.37	41.87	10.26	99.15	7.95
				Marginal yield, $\gamma_i = \frac{\lambda_2}{p_i x_i}$					
26	0.01	0.00	0.06	1.80	0.00	0.00	0.02	0.01	0.00
27	0.01	0.00	0.12	0.50	0.00	0.00	0.05	0.03	0.00
28	0.03	0.02	0.36	2.07	0.05	0.05	0.04	0.08	0.00
29	0.02	0.01	0.31	0.14	0.06	0.04	0.04	0.06	0.00
30	0.00	0.01	0.03	1.54	0.00	0.02	0.02	0.02	0.00
31	0.00	0.01	0.03	0.40	0.00	0.01	0.01	0.03	0.00
32	0.00	0.00	0.03	0.25	0.00	0.00	0.02	0.02	0.02
33	0.02	0.04	0.41	0.33	0.08	0.03	0.11	0.09	0.01
34	0.00	0.02	0.02	0.21	0.01	0.01	0.01	0.04	0.01
35	0.02	0.03	0.08	0.33	0.01	0.01	0.04	0.08	0.01
36	0.86	0.97	1.92	3.70	0.09	8.49	0.04	0.17	0.00
37	0.02	0.06	0.20	0.47	0.03	0.86	0.02	0.03	0.00
38	0.02	0.14	0.23	0.34	0.03	1.07	0.07	0.08	0.01
39	0.00	0.01	0.15	0.08	0.01	0.01	0.05	0.08	0.01
40	0.03	0.13	0.61	0.98	0.04	0.02	0.05	0.11	0.02