

# The impact of climate change on the optimal management of wetlands and waterfowl

by

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B.A., Concordia University, 2005

M.A., Memorial University, 2007

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## **Supervisory Committee**

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## **Abstract**

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The Prairie Pothole Region (PPR) of Western Canada is characterized by productive cropland, grasslands, and millions of ‘potholes’ caused by receding glaciers. These potholes fill up with water and form wetlands habitat that is a rich and valuable ecosystem, and is one of the most productive waterfowl habitats in the world. However, the social benefits from wetland ecosystems are not paid to farmers, whose lands support wetlands, leading farmers in the PPR of Canada to drain wetlands. Wetlands habitat in the PPR is also threatened by climate change, due to potentially drier conditions, as well as biofuel policies that are aimed at mitigating climate change (which increase the value of grains relative to wetlands). This research is comprised of four empirical papers that study the optimal level of wetlands retention, as well as the effect of potential future climate change on wetlands. The methods employed include bioeconomic modeling, which maximizes an economic objective (utility of cropping, harvesting ducks) subject to biological constraints (wetlands and waterfowl retention), as well as positive mathematical programming to develop a land use model. In the first paper, a previous bioeconomic model of optimal duck harvest and wetland retention is updated and extended to include the nonmarket value of waterfowl and the ecosystem service and

other amenity values of wetlands. Results indicate that wetlands and duck harvests need to be increased relative to historical levels. In the second paper, regression analysis is used to determine the casual effect of climate change on wetlands in the PPR. The model developed in the first paper is then adapted to solve the socially optimal levels of duck harvests and wetlands retention under current climate conditions and various climate change scenarios. Results indicate that the optimal number of wetlands to retain could decrease by as much as 38 percent from the baseline climate. In the third paper, the earlier bioeconomic model is extended to include cropping decisions. Further, the model is solved for disaggregated regions of the PPR. By including cropping decisions, this model can estimate the direct climate effects on wetlands and waterfowl management, as well as land use change due to biofuel policies. The model predicts that climate change will reduce wetlands by 35-56 percent from historic levels, with the majority of this change due to land use change. Wetlands loss is geographically heterogeneous, with losses being the largest in Saskatchewan. Finally, the fourth paper develops a multi-region Positive Mathematical Programming model that 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. This model has the advantage of modeling the trade off between all major land uses in the area and is also solved on a region basis. Results indicate that climate change could decrease wetlands in this area by as much as 34 percent; the results are spatially heterogeneous.

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# **Chapter 1**

## **Introduction**

Wetlands provide important ecosystem benefits to society, and also provide benefits in the production of waterfowl. Ecosystem benefits include filtration of agricultural and other pollutants (thereby improving quality of ground and even some surface waters), water for livestock and wildlife, opportunities for recreation, greenhouse gas storage, as well as non-market values such as visual amenities. The major challenge to the management of wetlands is that private landowners do not and, in most instances, cannot capture all of the values that wetlands provide – their value to society exceeds their value to private landowners. Because of the externalities associated with wetlands and their protection, public policies may be required to protect existing wetland areas and perhaps even restore lost wetlands.

Before implementing public policy to protect and/or restore wetlands, it is first necessary to determine whether existing wetlands area is indeed suboptimal from a social standpoint, and, second, whether government intervention is warranted. Government action to conserve wetlands has a cost, with government intervention warranted only if the costs of policies to conserve wetlands are less than the benefits to society. Environmental non-governmental organizations (NGOs), such as Ducks Unlimited, can bring together stakeholders (e.g., duck hunters, viewers of migratory waterfowl) to pay landowners for retaining and restoring wetlands. Nonetheless, government policies toward wetlands are important for preserving and enhancing wetland ecosystem services, and it is necessary to inform such policy by understanding whether wetlands retention is optimal, as well as where to focus wetlands conservation in the face of future threats.

This dissertation focuses on determining the socially optimal level of wetlands protection in Canada's Prairie Provinces. The primary concern relates to the conversion of wetlands area into cropland and their value in the provision of habitat for migratory waterfowl (although wetland ecosystem services are taken into account as well). The trade-off between these alternative uses of wetlands will become even starker should projected climate change lead to warmer temperatures and reduced annual precipitation in the study region. Therefore, in addition to understanding the optimal allocation of wetlands, the work studies how climate change may impact the optimal management of this natural resource. Bioeconomic modeling and mathematical programming (land use modeling) is used to investigate these questions.

The remainder of this introduction provides background to the issue of wetlands and wetlands management in the PPR. In addition to a general overview of the study region, the challenges of wetlands protection in this region and policy options for wetlands management are discussed. Second, the methodologies used to estimate optimal wetlands management are outlined and a discussion is provided as to how they have been used in the past. Finally, the introduction outlines the analysis of the dissertation, how each paper contributes to the overall goal of understanding optimal wetlands management in the face of climate change, and how the current work adds to the literature.

## **Wetlands and the Prairie Pothole Region of Western Canada**

Canada's Prairie Pothole Region (PPR) is part of the pothole region of North America's Great Plains (Figure 1.1), which was once the largest grassland area in the world. Receding glaciers from the last ice age left behind millions of shallow

depressions, which fill up with water each year. These shallow ponds, surrounded by grassland for cover, provide the perfect nesting grounds for waterfowl. Although the Canadian PPR represents a mere 10% of North America's waterfowl breeding habitat, the region produces over 50% of the continent's duck population (Baldassarre et al. 1994). Since the PPR also accounts for roughly 60% of Canada's agricultural output (Statistics Canada 2006), intense competition exists between private economic interests and public benefits in this region. Not surprisingly, wetlands numbers have been in decline due to intensification of agricultural production. Since ducks rely on the grassland area for breeding habitat, and the most important impact on duck populations is nest success and hen mortality during breeding (Ducks Unlimited Canada 2011), duck populations have also been in decline due to a loss of wetlands. This clear relationship between wetlands and waterfowl can be observed in Figure 1.2. North American waterfowl populations have fallen from some 35 million when populations first began to be monitored in the early 1950s to almost 15 million by the end of the first decade of the new century – a decline of more than 50 percent (U.S. Fish and Wildlife Service 2010a, 2010b). According to Ducks Unlimited Canada, between 50 to 90 percent of potholes have been degraded in some regions and nearly 194,000 acres of native grasslands have disappeared. Currently, the PPR is the number 1 of 25 most important and threatened waterfowl habitats in North America (Ducks Unlimited Canada 2011).



Figure 1.1: Prairie Pothole Region of North America

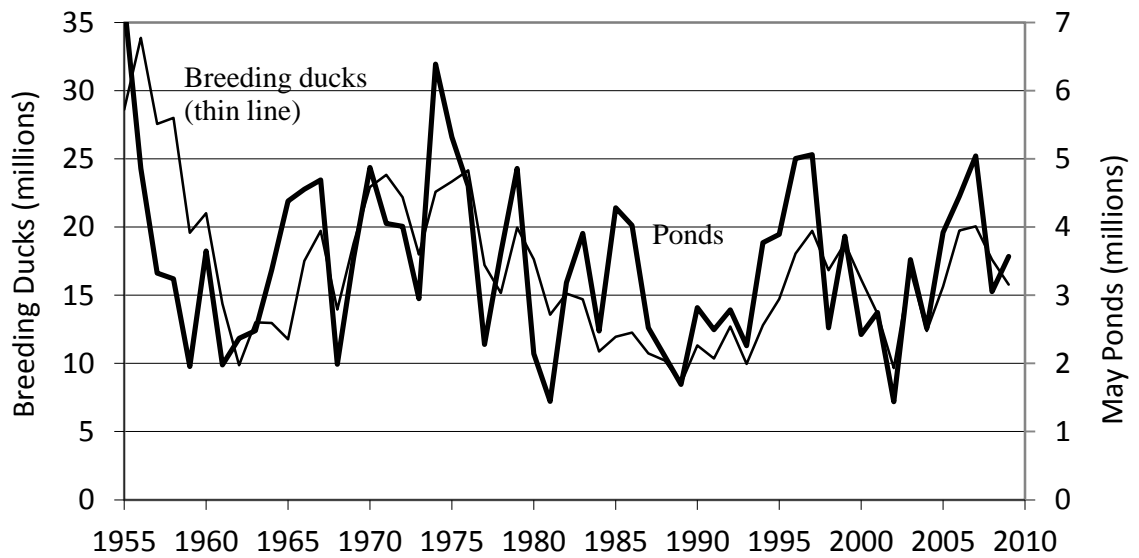
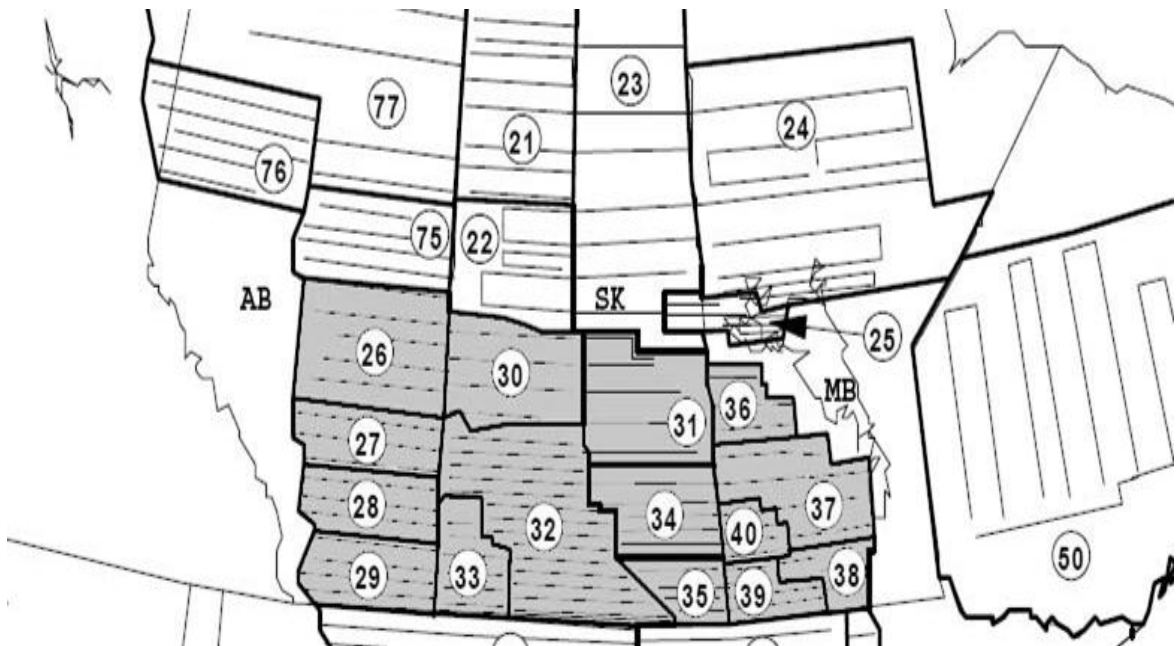


Figure 1.2: Relationship between Wetlands and Waterfowl in Canada's Grain Belt, 1955-2009

The U.S. Fish and Wildlife Service monitors waterfowl populations. The entire pothole region in Figure 1.1 is divided into strata, which are used to organize waterfowl population data as land and climate characteristics vary across this vast region. Strata 26 through 40 are located in western Canada's southern grain belt as indicated in Figure 1.3. Also shown in Figure 1.3 are 'transects' that biologists use to enumerate waterfowl populations. Transects are laid out in a pattern that avoids double counting of birds, and biologists count birds along the same transects each year to ensure continuity and reliability of samples.



*Figure 1.3: Transects and Strata of the Waterfowl Breeding Population and Habitat Survey*  
 Source: Wilkins and Cooch (1999, p.38); U.S. Fish and Wildlife Service (2010, p.60)

## **Threats to wetlands**

The two biggest threats to wetlands and the waterfowl populations they support in the PPR are agricultural development and potential increased drought due to climate change. The remainder of this sub-section discusses these threats on wetlands in more detail.

### *The effect of cropping on wetlands and waterfowl*

It is well documented that agricultural production has led to a reduction in wetlands and waterfowl in the PPR (Watmough and Schmoll 2007). My research examines the effect of agricultural land use on wetlands as climate changes in Chapter 4. In this introductory section, the relationship between agricultural land use and wetlands is examined more generally, and an empirical examination of the effects of agricultural land use on wetlands waterfowl populations is provided.

In Figure 1.4, time series of cropland acreage and waterfowl numbers for the PPR are provided; the data illustrate a possible negative relationship, especially after the 1970s. The picture is less clear when breaking things down into type of cropland and its relationship to wetlands as opposed to duck populations, although the two track fairly closely as indicated in Figure 1.2.

In Figure 1.5, seeded area and summerfallow area is graphed along with May pond counts for the period 1955-2009. It is not clear that either seeded area or summerfallow explains pond counts. What about the role of agricultural subsidies, which became important beginning in the early 1970s? A plot of agricultural subsidies and wetlands is provided in Figure 1.6. By conducting a regression analysis, we can

determine to what extent the factors in Figures 1.5 and 1.6 impact wetlands. Upon regressing May ponds on seeded acreage, summerfallow area and the per cultivated hectare agricultural subsidy, we find that agricultural subsidies do indeed have a negative impact on wetlands, but that the other variables do not. The OLS regression result is as follows (with t-statistics in parentheses):

$$\text{Ponds} = 7.45 - 0.12 \text{ Seeded} - 0.14 \text{ Fallow} - 0.01 \text{ Subsidy}, R^2=0.08 \quad (1.1)$$

$$(2.57) \quad (-1.18) \quad (-1.30) \quad (-1.88)$$

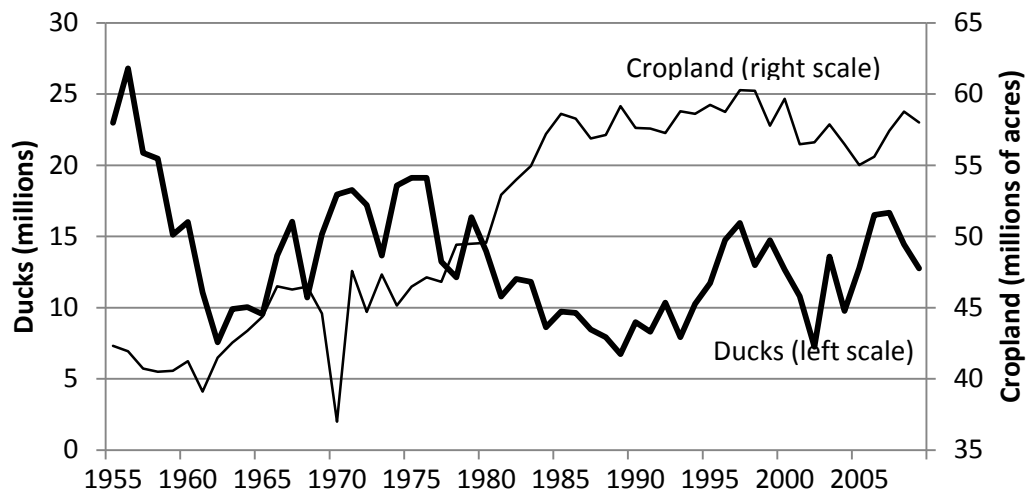


Figure 1.4: Cropland Acreage and Duck Populations, 1955-2009

Although the signs on the regressors have the expected signs, only the subsidy variable is statistically significant (at the 10% level). We see, therefore, that agricultural production, and particularly agricultural subsidies do have a statistically negative impact on wetlands; the problem is that very little of the variation in wetlands area is explained by agricultural programs or cropped area (seeded plus summerfallow area) in this

regression. Nonetheless, we do know that wetlands area has decreased, and that it comes at the expense of agricultural production.

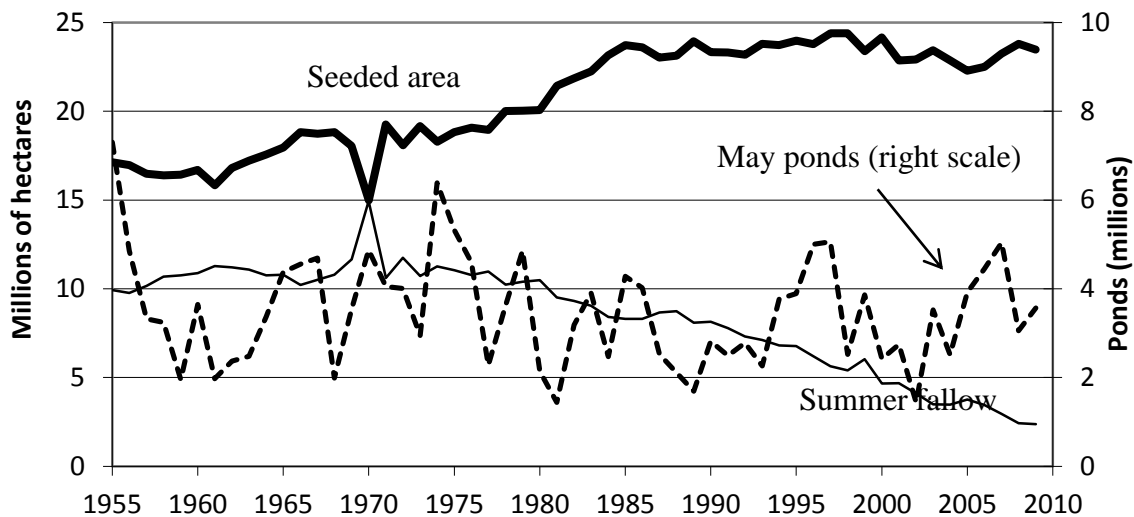


Figure 1.5: Seeded Area, Area in Summerfallow and Wetlands Area, 1955-2009

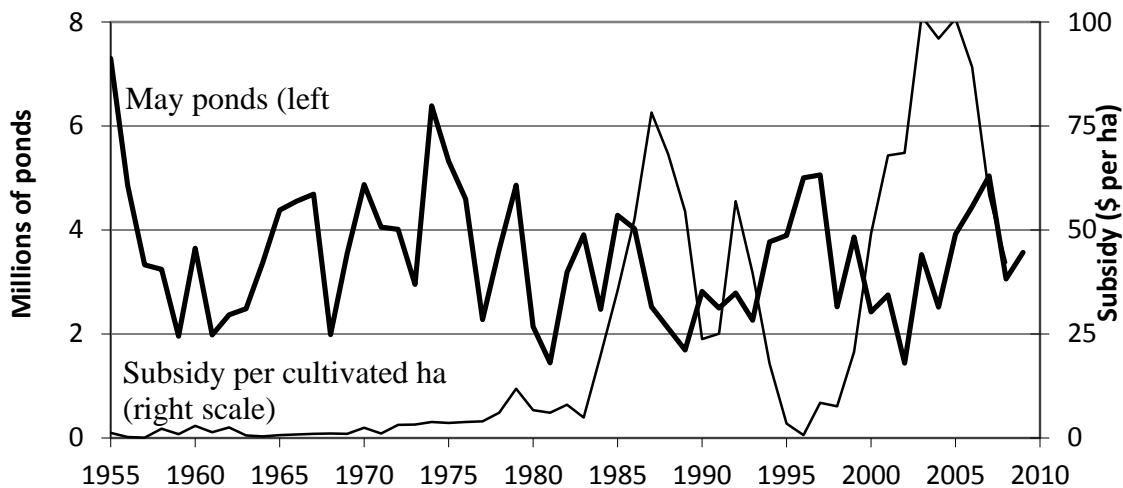


Figure 1.6: Agricultural Subsidy Level and Wetlands Area, 1955-2009

*The effect of climate on wetlands*

Climate change is the other major threat to wetlands, and is the focus of this dissertation. Climate factors are important in explaining wetlands area from one year to the next, but were ignored in the simple OLS regression provided above. One reason why climate is important relates to the measure used for wetlands, namely, May pond counts. While July ponds are likely more indicative of permanent wetlands, researchers have relied solely on May ponds because they provide a much better statistical explanation of duck populations than July ponds (see, e.g., van Kooten et al. 2011; Hammack and Brown 1974; Brown and Hammack 1973); this is also evident from Figure 1.2. Indeed, the U.S. Fish and Wildlife Service, the agency that tracks ponds, has altogether stopped using the July ponds measure. Nonetheless, many May ponds are temporary, found in low lying areas on fields, especially pasturelands, and are thus highly correlated with the timing of snow melt and spring precipitation – climate or weather factors.

Weather factors vary considerably across the region, with much drier conditions experienced in the southwest corner of the region (strata 28, 29 and 33) than in the northeast (e.g., strata 34 and 36). Annual and growing season precipitation increase along a line from southwest to northeast, while growing season length and growing degree days generally decline as one travels from south to north. These trends are not linear, however. Nonetheless, sub-region differences in the grain belt are important and need to be taken into account. Fewer wetlands are found in drier regions (e.g, strata 29 and 33), but agriculture also tends to be less intensive except where there is irrigation, which is the case especially in stratum 29. Because these differences in climate impact agricultural land use, it is important to take into account agricultural activities and agricultural rents

in the analysis of wetlands and migratory waterfowl. It is also important to understand how climate and potential climate change will impact wetlands differently across different regions of the PPR.

Climate change could result in substantially drier conditions and increased incidents of drought in Canada's grain belt during the 21<sup>st</sup> Century. Indeed, regional climate models predict that temperatures could rise by 1.8°C to 4°C in the prairie pothole region, while precipitation might range from a decrease of 5 % to an increase of 10% (IPCC, 2007). A drier climate will reduce the number of wetlands, which will have an adverse impact on agricultural ecosystems and the region's ability to produce waterfowl, as is clearly demonstrated by the high correlation between wetlands and breeding duck populations seen in Figure 1.2.

Wetlands are also impacted by policies that seek to mitigate climate change, particularly policies related to the enhanced production of biofuels. Such policies are like a subsidy, and increase the value of agricultural land (such as crops in canola) relative to wetlands. Yet, it turns out that such programs might even increase overall greenhouse gas emissions (Crutzen et al. 2008), lead to deforestation and conversion of marginal lands to cropland (Searchinger et al. 2008, 2009), and, in the prairie pothole region, result in the degradation of wetlands. The impacts of both climate change and climate change policies on wetlands are investigated in Chapters 3, 4 and 5.

### *Wetlands conservation*

Given the threats to wetlands discussed above, conservation plans have been put in place in order to manage the resource at optimal levels. We briefly introduce the main

conservation plan, leaving a more detailed discussion of policy tools to the conclusion section of the dissertation. There, we return to the topic of policy, and discuss the policy options available to government, based on the implications of this research.

Waterfowl management models have tended to focus primarily on the hunting benefits of waterfowl. While Adaptive Management plans have used wetlands numbers to formulate hunting seasons, the ecosystem value of wetlands are often considered extraneous to the determination of hunting season length and bag limits (the tools of waterfowl management). Recognizing that the majority of hunters are located in the United States while the preponderance of breeding habitat is in Canada, the 1986 North American Waterfowl Management Plan (NAWMP) (U.S. Department of Interior and Environment Canada 1986) was implemented as a mechanism by which the U.S. could compensate Canadian landowners for the positive externality that greater numbers of ponds in Canada provided U.S. hunters.<sup>1</sup> However, NAWMP was criticized for, among other things, simply offsetting the negative impacts of extant Canadian agricultural subsidies (van Kooten 1993b).

A variety of wetland conservation activities have been undertaken by public and private agencies since the 1890s (Porter and van Kooten 1993), but the establishment of the North American Waterfowl Management Plan in 1986 constituted the first continental effort to restore waterfowl populations – to levels seen in the mid 1970s (CWS 2004).

---

<sup>1</sup> The focus of NAWMP was not only on provision of ponds. The program provided payments to farmers for providing dense nesting cover on lands that would otherwise be cropped, thereby enhancing the ability of waterfowl to reproduce. Ideally sites are to be fenced to keep out predators, but payments are usually inadequate. See van Kooten and Schmitz (1992) and van Kooten (1993a, 1993b) for a more detailed discussion of these issues.

Since its inception, over \$1.5 billion has been used in conservation efforts across Canada with more than half of these funds directed to the prairies (NAWMP Committee 2009). In the PPR where the overlap between the best waterfowl habitat and the best agricultural lands can be as high as 91 percent (Bethke and Nudds 1995), it is not surprising that the primary conservation strategy is land securement: “The protection of wetland and/or upland habitat through land title transfer or binding long-term (minimum 10-year) conservation agreements with a landowner” (NAWMP Committee 2009). To date, over six million acres have been secured and an additional two million acres are targeted over the next 10 years (NAWMP Committee 2009). The results of this research will help inform government policies and conservation efforts (including NAWMP) on the level of wetlands restoration that is necessary, and where wetlands retention will be threatened in the face of climate change.

## **Methodological Overview**

The purpose of this research is to determine the optimal allocation of wetlands in the Prairie Provinces, under current conditions as well as in the face of climate change. The methods employed are bioeconomic modeling and positive mathematical programming, and this section provides an overview of each method. This section also outlines how these methods have been used in the literature, in the context of wetlands management or otherwise. The current section focuses only on the methodological overview, leaving literature reviews regarding the effects of climate change on wetlands to each of the four main chapters of this dissertation. A literature review for the effect of climate change on wetlands is found primarily in the literature review of Chapter 3.

## Dynamic optimization and bioeconomic modeling

### *Overview*

Natural resource economics problems determine the optimal allocation of scarce resources by maximizing the benefit derived from the resource subject to resource and other constraints. Non-renewable resource problems solve the optimal rate of extraction based on maximizing economic rents subject to the stock of the resource. In renewable resource problems, economists maximize the utility from extracting, or harvesting the resource, while accounting for the regeneration of the resource. Such problems rely on mathematical optimization methods, and approaches range from analytic to numeric, from deterministic to stochastic, from static to dynamic, and from non-spatial to spatial (e.g. Dasgupta and Maler 2004; Miranda and Fackler 2002; Bateman et al. 2006; Weintrub et al. 2007; Sanchirico & Wilen 2006, 2008; van Kooten & Bulte 2000; Wilen 2007). Optimization is briefly discussed below, focusing primarily on the case of discrete, dynamic optimization, as used in the current research.

Static optimization problems maximize an objective function, subject to constraints. The static problem is solved for one period only. Assuming the objective and restrictions are reliant on the variables  $x$  and  $y$ , the optimization problem is as follows:

$$\text{Max } U(x, y) \tag{1.2}$$

Subject to

$$f(x, y) \leq c \tag{1.3}$$

Where  $U(x, y)$  is a concave function and  $f(x, y)$  is a convex function. A solution can be found by solving the following Lagrange function:

$$L = U(x, y) + \lambda(c - f(x, y)) \quad (1.4)$$

where  $\lambda$  is the lagrange multiplier, or the marginal utility gained from relaxing the constraint by one unit. A solution is obtained by setting the derivative of the function with respect to each variable equal to zero, and solving the resulting system of equations. Specifically, in most economics applications, all variables are required to be non negative, and the following Kuhn-Tucker conditions must be satisfied in order for a point to be a maximum:

$$\frac{dL}{dx} \leq 0 \quad \text{and} \quad \frac{dL}{dx} x = 0 \quad (1.5a)$$

$$f(x, y) \leq c \quad \text{and} \quad \lambda(f(x, y) - c) = 0 \quad (1.5b)$$

A more detailed mathematical explanation can be found in any standard graduate microeconomic text (such as Varian 1992).

Dynamic optimization, or optimal control theory, solves a similar problem over time, which can be infinite. The optimal solution is found in each period, which depends on the previous period as well, making the problem an intertemporal one. The discrete time version of this model is as follows:

$$\text{Max } \sum_{t=1}^{T-1} \beta^t U(x_t, y_t) + \beta^T Sx_T \quad (1.6)$$

$$\text{Subject to } x_{t+1} - x_t = f(x_t, y_t) \quad (1.7)$$

$$x_0 = c \text{ is given}$$

The objective is maximized over (T-1) periods, and the salvage value of the resource must also be taken into account in the final period (T).  $\beta^t$  is a period discount rate, which accounts for the fact that people discount the future value of the resource. In this instance,  $y_t$  is a control variable, or choice variable, whereas  $x_t$  is the state variable (level of resource). When deciding on the optimal extraction of a resource, planners must take into account the change in the stock of the resource; condition (1.7) is a difference equation defining the change in the state variable from period t to (t+1) (Conrad and Clark 1987). The Lagrangian for this problem is:

$$L = \sum_{t=1}^{T-1} \beta^t U(x_t, y_t) + \beta^T Sx_T + \lambda_0(c - x_0) + \sum_{t=1}^{T-1} \beta^{t+1} \lambda_{t+1}(x_t - x_{t+1} + f(x_t, y_t)) \quad (1.8)$$

A solution is obtained by taking the derivative of this function with respect to  $y_t$ ,  $x_t$  and  $\lambda_t$  in each period. These maximum conditions can be summarized as follows:

$$\frac{\partial L}{\partial y_t} = 0 \Rightarrow \frac{\partial U}{\partial y_t} = -\beta \lambda_{t+1} \frac{\partial f}{\partial y_t}, \quad \forall t = 0, \dots, T-1 \quad (1.9)$$

$$\beta \lambda_{t+1} - \lambda_t = -\left[ \frac{\partial U}{\partial x_t} + \beta \lambda_{t+1} \frac{\partial f}{\partial x_t} \right], \quad \forall t = 0, \dots, T-1 \quad (1.10)$$

$$x_{t+1} - x_t = f(x_t, y_t), \quad \forall t = 0, \dots, T-1 \quad (1.11)$$

$$x_0 = c \quad (1.12)$$

$$\lambda_T = S'(x_T) \quad (1.13)$$

Equation (1.9) is a maximum principle; equation (1.10) is a co-state equation, describing how the current value of a resource must equal the future discounted value. Equation (1.11) is a state equation, whereas equations (1.12) and (1.13) are transversality conditions. This problem can also be represented as a current value Hamiltonian, and also in continuous time. For specific examples, see Conrad and Clark (1987).

Mathematical bioeconomics is a subset of the optimal control theory presented above, applied to renewable resources, and was formalized by Clark (1990). Examples of renewable resources include fisheries and other wildlife (populations reproduce) and forestry (replanting of timber). Changes in quality or quantity of the stock of these resources will impact the economic utility associated with resource extraction. To effectively manage these resources is to account for changes in the stock of the resource, and to understand how the stock replenishes. Mathematical bioeconomics takes into consideration not only economic questions (revenue, cost, etc) but also the impact of this demand on the resource. Bioeconomic models maximize an objective function, subject to biological, technical, socioeconomic or political constraints.

Mathematical bioeconomics uses the same framework as the discrete dynamic optimization problem outlined above. In particular, one maximizes an objective such as (1.6) subject to a constraint (1.7). The constraint explains how the stock of the resource is changing over time, due to natural changes in the variable (e.g., biological functions and the environment), as well as exploitation (e.g., harvesting the control variable), which can deplete the stock. The main difference in bioeconomic modeling from standard optimal control theory is how the constraint is specified, and the fact that the modeler must establish some tradeoff between economic goals and environmental or biological goals. When biological populations are involved, the constraint (1.7) can be written as follows:

$$x_{t+1} - x_t = f(x_t) - y_t \tag{1.14}$$

where  $f(x_t)$  is a function representing the natural growth rate of the population, and  $y_t$  represents the rate of harvest (Clark 1990).

Growth functions have been studied extensively in biological research, to understand the behavior of populations and the variables affecting them. Bioeconomic models bring these bio-physical functions into the same framework as economic maximization to understand how to sustainably manage a resource, by maximizing utility subject to maintaining healthy populations. The primary function used to estimate the growth function of populations is the logistic growth function, which is often applied to fisheries. In discrete time, the logistic growth function can be represented as follows:

$$x_{t+1} - x_t = rx_t \left(1 - \frac{x_t}{K}\right) \quad (1.15)$$

where  $x_t$  is the resource (or population),  $r$  is the intrinsic growth rate, and  $K$  is the carrying capacity of the resource. This expression can be broken into two parts, birth ( $rx$ ), and crowding out ( $\frac{rx^2}{K}$ ); since when the populations gets too high, they will be competing for the same resources, there will be some maximum level of the population. Other growth functions used in the literature include multiplicative and Beverton-Holt, however the logistic form remains popular.

### *Bioeconomic literature*

Bioeconomic models have been used extensively in the natural resource economics literature. Methods vary somewhat, from pure biological functions with economic arguments added, to economic optimization problems with biophysical elements added in, such as the model described above (Brown 2000). Typically, wildlife management models fall in the latter category and the following review focuses on several such studies. First, a general review of the types of models that have been solved using bioeconomics is provided. The attempt is to demonstrate the breadth of

bioeconomic modeling. Further, several key bioeconomic studies that have been used to understand wetland and waterfowl management are discussed.

Bioeconomic models are most widely applied to the area of fisheries management and marine reserves. Bioeconomic models that maximize the revenue from catch subject to the population dynamics of fish species strive to optimally manage the resource by maximizing revenue without overfishing. A review of bioeconomic models used to study marine reserves can be found in Grafton et al. (2005), while an overview of bioeconomics models in fishery economics can be found in Munro (1992).

Bioeconomic models have been applied to several other wildlife management problems. Boman et al. (2003) employed a spatial dynamic bioeconomic model of wolves in Sweden to develop spatially differentiated conservation policies. Rondeau and Conrad (2003) use a bioeconomic model to manage urban deer in Irondequoit, NY. They argue that authorities should harvest as many deer as safety constraints allow, rather than designing management strategies based on steady state values. Several studies have used bioeconomic models to study elephant population dynamics and illegal trade of ivory (Skonhofs and Solstad 1996; van Kooten 2008). van Kooten (2008) uses a dynamic bioeconomic model of ivory trade to examine conservation payments, tourism benefits, quota regimes and a trade ban on the protection of the African elephant. Results indicate that “Unless the contribution of living elephants to the wellbeing of citizens in range states (via tourism revenues) or in rich countries (through their willingness to pay to ensure the existence of elephants now and in the future) is taken into account, the elephant is most likely to remain a species under threat of extinction”. Finally, Olausson and Skonhofs (2005) apply bioeconomics to the management of moose populations.

Several other studies use bioeconomic methods to study the tradeoff between lands designated as protected areas for wildlife versus land used for revenue generating activities. This topic is related to the work done in Chapters 4 and 5 of this dissertation, which evaluates the tradeoff between lands for wetlands and land for agricultural production. Johannesen (2007) used a bioeconomic model of protected area expansion for regions where hunter-agrarian communities were located close to the borders of protected areas. Skonhofs (1998) and Johannesen and Skonhofs (2004) used bioeconomic models that examined the tradeoff between the protection of wildlife and agricultural production in rural communities near national parks in Africa. Similarly, Bulte and Horan (2003) "...develop a model of open access wildlife exploitation, habitat conservation and agricultural expansion, which is consistent with rural communities at the fringe of natural habitats in areas such as sub-Saharan Africa."

The preceding review demonstrates how bioeconomic models have been used in a range of situations to study the tradeoff between economic goals and biological and environmental conservation. Bioeconomics have been used extensively in the literature to study topics where economic activity threatens wildlife populations, habitat, or both. Wetlands and waterfowl management in the Prairie Pothole Region is one such case, where land used to produce waterfowl is in direct competition with agricultural land used to generate crop revenue. Draining wetlands for agricultural production removes a valuable ecosystem, but also threatens the wildlife population (waterfowl) that it supports. Several studies have used bioeconomic modelling to study wetlands and waterfowl management.

Pioneering work by Gardner Brown and Judd Hammack (1973), Brown et al. (1976) and Hammack and Brown (1974) used optimal control methods and a discrete dynamic bioeconomic model to characterize optimal wetland and waterfowl retention in the Prairie Pothole Region of North America. Their bioeconomic model of migratory waterfowl used both Beverton-Holt and multiplicative production functions for population growth functions, estimates of duck survival rates and results from a U.S. survey of duck hunters to determine optimal levels of duck harvests and wetland protection. They concluded that there were too few wetlands (by some 18% to 55%) in Canada's southern Prairie Provinces. More detail is provided in Chapter 2.

Johnson et al. (1997) developed a similar bioeconomic model of duck hunting in the Prairie Pothole Region, using a stochastic dynamic programming framework to address uncertainty related to random environmental and population variations and incomplete control over hunters' decisions. They find that, as wetlands in Canada's pothole region increase, the optimal management strategy is to have a more liberal hunting regime (longer hunting seasons and higher bag limits).

Another bioeconomic model of wetlands in the Prairie Pothole Region is due to van Kooten (1993a). This study used an optimal control model to investigate the effect of agricultural support programs on wetlands conversion. In this model, a typical farmer maximizes revenue subject to three constraints representing the change in the stock of marginal lands from one year to the next, the maximum annual amount of marginal land that can be converted to crop production, and a total land constraint, respectively. It is found that agricultural subsidies lead to 24% more conversion of unimproved land and

that “payments to farmers to maintain waterfowl habitat are higher they would have to be in the absence of grain support payments”.

Rashford and Adams (2007) and Rashford et al. (2008) also used bioeconomic methods and focused on waterfowl management in the Prairie Pothole Region. Rashford and Adams (2007) used waterfowl as an example to better understanding the cost-effectiveness of species conservation programs. The bioeconomic model minimizes ecosystem management costs subject to a biological response function, mapping conservation activities to species populations, while also accounting for landscape characteristics. They use the example of waterfowl, and base the biological functions on the Mallard Productivity Model. Results indicate that direct conservation methods, such as predator control, are more cost-effective than primary land use conservation activities. They also find that cost-effectiveness can be improved by accounting for a broad range of land-use activities, by accounting for heterogeneity in landscape and by accounting for interactions between conservation activities.

Rashford et al. (2008) construct a static bioeconomic production model to understand how to achieve management goals at least cost, focusing on mallards in the United States PPR. Similar to the above study, the focus is on determining the least cost outcome of eight different conservation management activities. They use an economic optimization model to minimize the costs of management activities, and as constraints rely on a biological simulation model of breeding waterfowl to determine mallards biological response to management activities, as well as land use and other constraints. Results show that ecological response and economic costs jointly determined cost effective management plans. Further, the least cost management plans depend on the

chosen population objective. For instance, management plans may be cost effective for low levels of mallard production, but not at higher levels. Thus, management strategies must be clearly identified in order to find the least cost plan.

Other studies have used bioeconomic modeling to estimate wetlands or waterfowl in other contexts or regions. Miettinen and Huhtala (2005) specified an optimal control model of cereal crop production and grey partridge hunting values in Finland. They maximized returns to land used for crops as well as land that is conducive for bird habitat, subject to constraints on the grey partridge population. The goal was to derive economic instruments needed for enhancing biodiversity on farmland, such as subsidies for certain kinds of grains, herbicide tax and hunting licenses. Further, Whitten and Bennett (2004) use a bioeconomic model to determine the optimal allocation of wetlands on private lands in the Murrumbidgee River Floodplain in New South Wales, Australia.

### **Positive mathematical programming**

Bioeconomic models have been used to analyze the tradeoffs between economic goals and biological conservation, and to examine the tradeoffs between agricultural production and wildlife habitat. Mathematical programming can also be used to estimate the tradeoffs between different land uses, including those used for agricultural production versus those suitable as wildlife habitat. Linear programming (LP) models have historically been used to calibrate land use, however positive mathematical programming (PMP) has the advantage of calibrating land use to actual observed levels. PMP methods are currently very popular, due to the exact calibration mechanism, data limitations (that mathematical programming models can deal with better than econometric models) and

the need to model behavioural functions subject to technical, economic, policy and environmental constraints (de Frahan et al. 2007). PMP models are also particularly useful in examining agricultural and environmental or ecological tradeoffs – one can calibrate land use to observed acreage and determine the effect of different policies by changing parameters. In the current context, one can change climate conditions to determine the effect of climate change on land use and in particular, wetlands. In this section, we provide an overview of LP and PMP, and provide a brief overview of developments in the PMP methodology. There are several applications of PMP that examine agriculture and the environment, and an overview of this literature is provided in the introduction of Chapter 5. To our knowledge, no studies to date use this method specifically to look at wetlands management.

LP models seek to maximize profit or minimize costs subject to a set of linear constraints. In agricultural economics, LP is used to maximize revenue from crop production, subject to resource constraints:

$$\text{Max } c'x \quad (1.16)$$

Subject to

$$Ax \leq b \quad (1.17)$$

$$x \geq 0, \forall i \quad (1.18)$$

where  $x$  is an  $(n \times 1)$  vector of production activities and  $c'$  is an  $(n \times 1)$  vector of net revenue from these activities (i.e.  $py-c$ , where  $p$  is price,  $y$  is average yield and  $c$  is marginal cost).  $A$  is a matrix of the technical coefficients of production (the amount of a given resource required per unit of  $x$ ); and  $b$  is the total amount of a resource that is

available. Equation (1.18) represents non-negativity constraints. The issue with this methodology is that model results will calibrate to the few most profitable land use activities, whereas several more may be observed. While one can force the model to bind to observed activities, this does not allow the modeller to run policy scenarios through the model. Rather, PMP provides a theoretically sound calibration mechanism to calibrate models to observed acreage, and allows for policy simulations.

The PMP method used in this research is based on the notion that any linear constraint can be modeled using a nonlinear cost or yield function. Thus, rather than adding arbitrary calibration constraints to an LP in order to replicate observed land use, the PMP method uses such constraints to specify an appropriate nonlinear yield (or cost) function, and the calibrated model then solves for observed values in all crops. The PMP method is implemented in three stages. The first involves maximizing net returns to land uses (as in the LP above), subject to resource and calibration constraints:

$$\text{Max } c'x \quad (1.19)$$

Subject to

$$Ax \leq b \quad (1.20)$$

$$x \geq 0, \forall i \quad (1.21)$$

$$x \leq x^o + \varepsilon, \forall i \quad (1.22)$$

where constraints (1.22) constitute the calibration constraints needed to implement PMP, with  $x^o$  the observed acreage in each land use and  $\varepsilon$  a perturbation term that is chosen to be a very small positive number.

The dual values from the LP described by (1.19), (1.20), (1.21) and (1.22) are then used in the second stage of the PMP calibration to estimate the parameters of a nonlinear yield function. The perturbation coefficient  $\varepsilon$  in equation (1.22) decouples the shadow prices for equations (1.21) and (1.22) ( $\lambda_1$  and  $\lambda_2$ ), and enables the dual values from equation (1.22) to be used to calculate the production function parameters. However, since the number of constraints exceeds the number of activities, at least one of the calibration dual values,  $\lambda_2$ , will be zero. This least profitable activity is considered a marginal crop, where the calibration constraint ( $\lambda_2$ ) does not bind and the activity is constrained only by the land use equation ( $\lambda_1$ ) in (1.21). In particular, using the notion that the dual values are given by  $A\lambda_1=c$ , Howitt (1995) partitions the problem into profitable and marginal activities and proves that if there are  $n$  activities, for the  $n-m$  profitable activities, the dual value will be  $\lambda_2 = c - A'\lambda_1$ , whereas  $\lambda_2=0$  for the  $m$  marginal activities and the dual value is determined entirely by  $\lambda_1$ . (Appendix B, Howitt 1995). That is, suppose we partition the problem into preferred ( $x_p$ ) and marginal ( $x_m$ ) activities:

$$\text{Max } c_p x_p + c_m x_m \quad (1.23)$$

Subject to

$$Ax \leq b \quad (1.24)$$

Equation (1.24) can be partitioned into:

$$\begin{pmatrix} B & N \\ 0 & I \end{pmatrix} \begin{pmatrix} x_m \\ x_p \end{pmatrix} = \begin{pmatrix} b \\ x_p^0 + \varepsilon \end{pmatrix} \quad (1.25)$$

And using  $A'\lambda_1=c$ , the resulting dual values are found to be:

$$\begin{matrix} \lambda_{2m} \\ \lambda_{2p} \end{matrix} = \begin{bmatrix} B'^{-1} & 0 \\ -NB'^{-1} & I \end{bmatrix} \begin{matrix} c_m \\ c_p \end{matrix} \quad (1.26)$$

$\lambda_{2m}$  is only determined by  $A'c_m$  (where  $B'^{-1}$  is m portion of the partitioned A), whereas  $\lambda_{2p}$  is determined by  $A'c_m$  and  $c_p$  :  $\lambda_{2p} = c_p - N' B'^{-1} c_m$ . The right hand side is the difference between the gross margin of the calibrating activity  $c_p$  and the equivalent gross margin obtained from the less profitable marginal cropping activities  $c_m$  (Howitt 2005).

Now, assuming a quadratic yield function,  $y_i = (\beta_i - \gamma_i x_i) x_i$ , Howitt (1995) shows that the dual values on the calibration constraints,  $\lambda_2$  in equation (1.22), are equal to the difference between the value of the average and marginal products of land. Thus,  $\gamma_i$  and  $\beta_i$  are derived as follows:

$$\lambda_2 = VAP - VMP = p_i(\beta_i - \gamma_i x_i) - p_i(\beta_i - 2\gamma_i x_i) = p_i \gamma_i x_i \quad (1.27)$$

$$\gamma_i = \frac{\lambda_2}{p_i x_i} \quad (1.28)$$

$$\beta_i = y_i + \gamma_i x_i \quad (1.29)$$

Given the dual values for each calibrated land use ( $\lambda_2$ ), as well as data on p, y and x, one can calibrate nonlinear yield functions that represents the decision of land owners. Note that if calibrating the PMP model on costs rather than on yields (production), and employing a quadratic cost function, the dual values are interpreted as the difference between the marginal cost and average cost of production.

For marginal crops, the calibration constraint does not bind and the activity is constrained only by the land use equation; when  $\lambda_{2i}$  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  $\gamma_i=0$ . 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. Alternatively, one can use the elasticity of supply rather than crop variation in order to estimate the dual value on marginal crops. For the first-order conditions to hold, a decrease in  $\lambda_1$  will be offset by an increase in the value of  $\lambda_2$  for the marginal crop. This new value of  $\lambda_2$  for the marginal crop,  $\bar{\lambda}_{2,marginal}$ , can be used to calculate the nonlinear yield function for the marginal activity. All other  $\lambda_{2i}$  values must be adjusted by  $\bar{\lambda}_{2,marginal}$ .

In the third step, the nonlinear yield functions are used to solve the PMP problem:

$$\text{Max } c'x \quad (1.30)$$

Subject to

$$Ax \leq b \quad (1.31)$$

$$x \geq 0, \forall i \quad (1.32)$$

where  $c$  is now  $(p(\beta_i - \gamma_i x_i) - c)$  for a quadratic yield function, opposed to  $(py - c)$  which was assumed in the above LP model.  $y$  is the average yield and  $\beta$  and  $\gamma$  are nonlinear yield parameters. Using only the resource constraint (1.31), and non-negativity constraints (1.32), the solution replicates the observed allocation for a base year, since the estimated nonlinear yield functions capture farmers' decisions to plant certain crops even though they might not seem economically profitable, such as risk, land quality heterogeneity and that land suitability varies across space for a given crop. Since the

model has a theoretically sound calibration mechanism, it can reliably estimate the impact of policies or any changes in the parameters of the objective function or changes in resources. For different scenarios, only the parameters in (1.28) need to be adjusted. In the current context, we can calibrate to observed wetlands and change the parameters of the yield function based on changing weather conditions to estimate how climate change might impact land use, and in particular, wetlands.

The PMP model presented here has been extended in several ways over the past decade. Some major recent developments are highlighted below, however most of the extensions are beyond the scope of the current application. De Frahan et al. (2007) provide a much more detailed review of recent developments, including a discussion of the following issues: the under-identification problem (Heckeley and Britz 2000; Paris and Howitt 1998; Golan et al., 1996); the unequal treatment of preferred and marginal activities (Rohm and Dabbert 2003); accounting for greater competitiveness of closely related crops (Rohm and Dabbert 2003); incorporating risk (Paris 1997); expanding the PMP framework into a Symmetric Positive Equilibrium Problem (SPEP) to account for the use of a linear technology in limiting resources and the zero-marginal product for one of the calibrating constraints (Paris 2001; Paris and Howitt 1998); and the first phase estimation bias (Heckeley and Britz 2005; Heckeley and Wolff 2003).

One major development in the literature is the use of maximum entropy in PMP models (Howitt 2005, Chapter 9) to solve a shortcoming of the original PMP specification. The PMP solution assumes that the quadratic cost matrix is strictly diagonal, which implies that there are no cross effects between the planting of different crops. This is unrealistic, since farmers are aware of the interdependencies between

crops. However, one cannot typically estimate the full matrix of coefficients, since the problem is under identified. Using information theory and maximum entropy, Paris and Howitt (1998) determine all the  $[n + n(n + 1)/2]$  elements of the matrix using the Cholesky factorisation, even though there are only  $n$  observations. Using this estimator in the PMP model allows for competition and complementarity between activities in the calibrated quadratic variable cost function, while still being based on a single observation but using *a priori* information. Heckeley and Britz (2000) use a more general specification, and use additional observations from the same farm or region to collect information on second order derivatives.

A second major issue with PMP is that Heckeley and Wolff (2003) argue that there can be bias in estimating the dual values in stage one of the PMP method, and the calibrated parameter values might therefore also be biased. To avoid inconsistency between steps 1 and 3, Heckeley and Wolff (2003) suggest to “skip the first step altogether and employ directly the optimality conditions of the desired programming model to estimate, not calibrate, simultaneously shadow prices and parameters”. They use the Generalized Maximum Entropy (GME) procedure to illustrate this alternative to the original PMP model.

## **Outline of Research**

This section provides a detailed overview of the research goals, including a brief discussion of the purpose, methods, and scope of the investigation undertaken. An outline of the analysis of the dissertation is provided, as well as how each paper contributes to the literature and the overall goal of understanding optimal wetlands management in the

face of climate change.

The analysis begins in Chapter 2, where a bioeconomic model of duck hunting and wetlands protection is examined to demonstrate the optimal level of wetlands retention in the Canadian PPR. The bioeconomic model incorporates the amenity or ecosystem values provided by wetlands values and the viewing value of waterfowl.

In Chapter 3, the model of Chapter 2 is adapted to consider what level of wetlands would need to be protected in order to maximize social utility should climate change result in either wetter or drier conditions than those experienced during the last century. The relationship between climate and wetlands is estimated using linear regression models. This analysis focuses on direct climate effects and treats the PPR as one region.

In Chapters 4 and 5 we examine the regional impacts of climate change on agricultural land use and wetlands retention, and consider the total climate change impact on wetlands: a potentially drier climate as well as biofuel policies aimed at mitigating climate change. In Chapter 4, the previous bioeconomic of Chapter 2 is extended to include cropping decisions. Instead of a single state equation, the model has two state equations representing the population dynamics of ducks and the amount of wetlands. We use the model to estimate the total impact of climate change on wetlands and waterfowl from current conditions. The model is parameterized separately for each province and for each of the strata that are used for surveying waterfowl and wetlands.

Finally, in Chapter 5, a multi-region (strata) land-use model is developed for the PPR. Positive mathematical programming is used to calibrate the model to observed land uses for nine land uses. The subsequent model is then used to simulate both the impact of climate change on land use (including changes in wetlands) and that of biofuel policies

that seek to mitigate global warming.

The research in the four papers outlined above contributes to the literature on the impact of climate change on the wetlands management in several ways. The first paper provides an up to date analysis of the socially optimal level of wetlands retention, which includes the social benefits of wetlands. The next three chapters study the climate change impact on wetlands, which has not been studied in the context of bioeconomic modeling or positive mathematical programming. Further, the impact of biofuel policies on wetlands management has not been explored. The analysis in Chapter 3 estimates climate change effects using a bioeconomic model, but focuses only on direct climate change impacts, ignoring for now the effect of biofuels and regional impacts. This work demonstrates how climate change might impact the socially optimal level of wetlands retention. Chapters 4 and 5 explore the topic in more detail, estimating the total climate change effect, as well as regional effects. Chapter 4 develops a bioeconomic model that includes agricultural land use, and focuses on the socially optimal wetlands retention as both climate and land use (due to biofuel policies) change. The main limitation of this study is that it only includes two land uses (wetlands vs. crops). The fourth paper calibrates a model to observed land use, and is unique because it allows us to explicitly model the trade-off between all major land uses in the PPR as climate changes, providing a more complete analysis. PMP has been used for many agro-environmental policy questions. However, it has never been used to study wetlands management, although the current problem lends itself to the application of PMP very well.

## **Chapter 2**

# **Bioeconomic Modelling of Wetlands and Waterfowl in Western Canada: Accounting for Amenity Values**

### **Introduction**

Wetland ecosystems are important not only for producing waterfowl, but also for the ecosystem services they provide. Yet, drainage activities by farmers in Canada's southern Prairie Provinces over the past century have significantly reduced wetlands (Watmough and Schmoll 2007). This region, known as the prairie pothole region is also North America's duck factory, so loss of wetlands is a major concern because of the relation between wetlands (as measured by ponds) and waterfowl production (Figure 2.1). Wetlands are also threatened by projections indicating that the 21st century could be substantially drier in the pothole region than its predecessor (IPCC, 2007).

Waterfowl management models have tended to focus primarily on the hunting benefits of waterfowl. While Adaptive Management plans have used wetlands numbers to formulate hunting seasons, the ecosystem value of wetlands are often considered extraneous to the determination of hunting season length and bag limits (the tools of waterfowl management). Recognizing that the majority of hunters are located in the United States (Figures 2.2 and 2.3) while the preponderance of breeding habitat is in Canada, the 1986 North American Waterfowl Management Plan (NAWMP) (U.S. Department of Interior and Environment Canada 1986) was implemented as a mechanism by which the U.S. could compensate Canadian landowners for the positive externality

that greater numbers of ponds in Canada provided U.S. hunters.<sup>2</sup> However, NAWMP was criticized for, among other things, simply offsetting the negative impacts of extant Canadian agricultural subsidies (van Kooten 1993a).

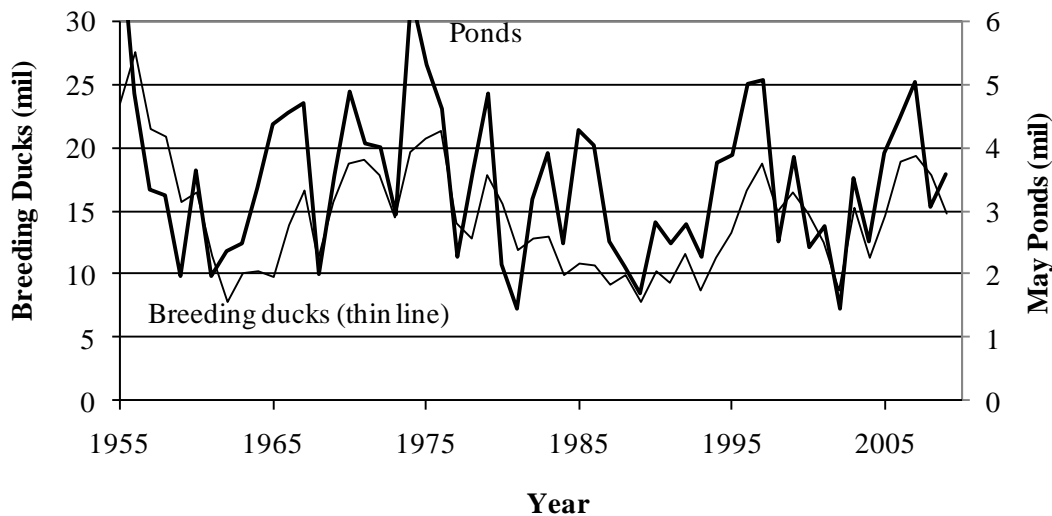


Figure 2.1: Relationship between Wetlands (May Pond Numbers) and Waterfowl in Canada's southern Prairie Provinces, 1955-2009

<sup>2</sup> The focus of NAWMP was not only on provision of ponds. The program provided payments to farmers for providing dense nesting cover on lands that would otherwise be cropped, thereby enhancing the ability of waterfowl to reproduce. Ideally sites are to be fenced to keep out predators, but payments are usually inadequate. See van Kooten and Schmitz (1992) and van Kooten (1993b) for a more detailed discussion of these issues.

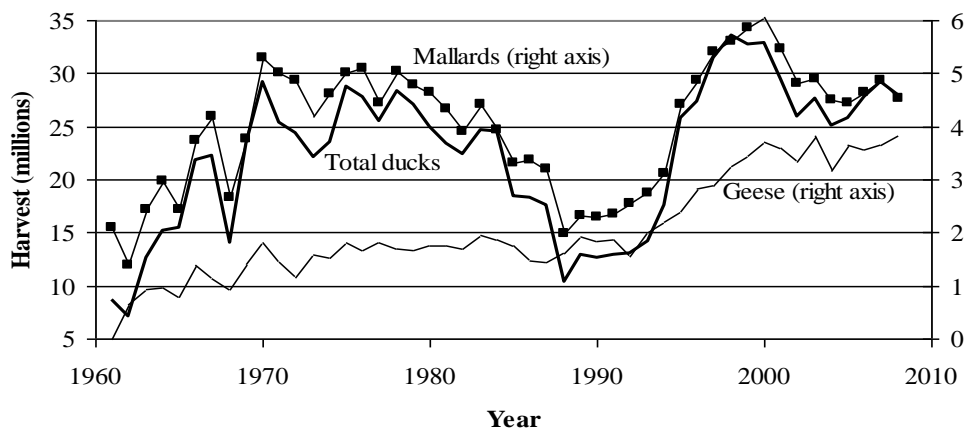


Figure 2.2: U.S. Harvests of Ducks, Mallards and Geese, 1961-2008

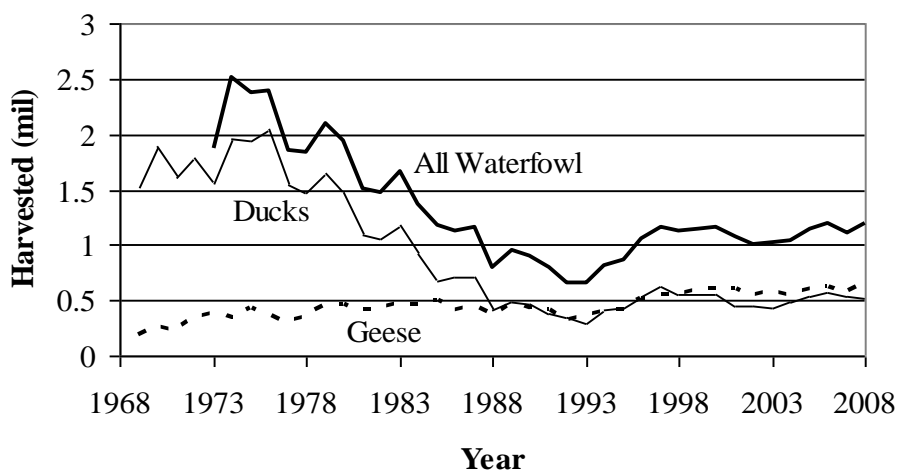


Figure 2.3: Harvests of Ducks, Geese and All Waterfowl, Canada's Prairie Provinces, 1969-2008

A pioneering waterfowl management model that sought to provide guidance to decision makers in setting hunting policy, including policy related to protection of wetlands, is due to Gardner Brown and Judd Hammack (Hammack and Brown 1974; Brown and Hammack 1973; Brown, Hammack and Tillman 1976). Their bioeconomic model of migratory waterfowl used a Beverton-Holt production function, estimates of duck survival rates and results from a U.S. survey of duck hunters to determine optimal

levels of duck harvests and wetland protection. They concluded that there were too few wetlands (by some 18% to 55%) in Canada's southern Prairie Provinces. In deciding optimal levels of waterfowl and wetlands, the authors ignored the possibility that waterfowl have non-use (e.g., viewing) value, while wetlands have a variety of use (ecosystem service) and non-use (e.g., visual) values outside of their role in producing waterfowl.

The objectives of the current paper are essentially threefold. First, given the pioneering nature and importance of the contribution made by Brown and Hammack (1973), and Hammack and Brown (1974), we re-examine their study by re-estimating their model using nearly 40 years of additional data and determine if their conclusions still hold. Second, we extend their model to include the nonmarket (in situ) benefits of waterfowl and the ecosystem use and non-use values of wetlands themselves. Finally, we compare the outcomes of a model that considers only hunting values of waterfowl with those of our extended model. We conclude with some observations regarding the opportunities and challenges that this line of inquiry poses, and directions for future research. The results of this model will be informative in their own right, but also provide a benchmark model from which to estimate the effect of climate change on wetlands.

Further, this work complements three recent studies of wetlands protection in Canada's grain belt. In one study, Pattison et al. (2011) used an internet survey device to determine the willingness to pay of Manitobans to conserve wetlands. They find that, despite a large annual WTP, the costs of restoring wetlands to their 1968 level would simply not be warranted, although retention and restoration of some wetlands would be socially desirable. Hill et al. (2011), and Yu and Belcher (2011), address the opposite side

of the issue – the willingness of landowners to participate in wetlands retention and restoration schemes. Yu and Belcher use a survey instrument to determine the payments farmers would need to participate in a 10-year program to protect wetlands, while Hill et al. use an actual reverse auction. Both studies focus on regions in Saskatchewan, and neither provides optimism about society's ability to protect let alone restore wetlands at low costs. Wetland retention and restoration are likely to prove costly, unless spatial targeting also proves cost effective. The current study employs some of these results in a broader investigation of the economics of retaining wetlands in western Canada's grain belt when faced with the threat of global warming.

### **Bioeconomic Model**

Brown and Hammack (1973), hereafter B&H, were the first to use mathematical bioeconomic models (Clark 1976) to address wetlands conservation. Such models optimize an economic objective function subject to technical, biological, socioeconomic and political constraints. B&H (1973) and H&B (1974) chose a model that could be solved analytically to provide insights, but they needed to solve it numerically to determine whether the optimal policy called for more or less wetlands. In their specification, they focused exclusively on duck hunting values, ignoring other waterfowl values and wetland benefits. We begin with a variant of the H&B model, and then expand it to include the in-situ amenity value of waterfowl and, importantly, the ecological service and other amenity values of wetlands.<sup>3</sup>

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<sup>3</sup> Johnson et al. (1997) used a stochastic dynamic programming framework to address uncertainty related to random environmental and population variations and incomplete control over hunters' decisions. They Cont.

B&H (1973) and Brown et al. (1976) specify a discrete bioeconomic optimal control model of duck hunting. They postulate a social planner whose objective is to maximize benefits to hunters minus the costs of providing wetlands:

$$\sum_{t=1}^T [v(h_t, y_t, Z_t) - C(W_t)] \rho^t, \quad (2.1)$$

where  $v(h_t, y_t, Z_t)$  is a function describing the annual benefits derived from duck hunting, which is a function of the number of ducks harvested ( $h$ ), per capita income of duck hunters ( $y$ ), and such things as age, gender and outdoor experience that characterize duck hunters ( $Z$ );  $C(W_t)$  is the annual cost of providing the potential for  $W$  amount of wetlands (measured by the number of ponds); and  $\rho = 1/(1+r)$  is the discount factor with  $r$  the discount rate used by the hypothetical planner. The length of the planning horizon is  $T$ , and could possibly be infinite. In the H&B model, harvest levels by hunters and the number of ponds are decision variables.<sup>4</sup>

H&B's objective function (2.1) can be extended by bringing in two types of amenity values – one is related to the nonmarket (non-use) benefits of waterfowl, while the other takes into account the ecosystem service and non-use values of wetlands themselves. The modified objective function is:

$$\sum_{t=1}^T [v(h_t, y_t, Z_t) + \alpha D_t + B(W_t) - C(W_t)] \rho^t, \quad (2.2)$$

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found that, as wetlands in Canada's pothole region increase, the optimal management strategy is to have a more liberal hunting regime (longer hunting seasons and higher bag limits). While uncertainty is important, we leave this to future research as our focus is primarily on B&H's pioneering work.

<sup>4</sup> H&B multiply  $v(\cdot)$  by the number of hunters, the control variable if bag limits and average take per hunter are constant. Here  $v(\cdot)$  is simply the benefit to all hunters.

where  $D_t$  refers to the population of May breeding ducks in year  $t$ , while  $\alpha$  is the annual amenity value of a duck, which could be positive for small numbers of ducks and negative for large numbers (e.g., if large numbers lead to crop depredation). To keep things simple, we assume the amenity value is a positive constant.  $B(W_t)$  is a wetlands ecosystem benefit function with  $\partial B/\partial W_t > 0$  and  $\partial^2 B/\partial W_t^2 \leq 0$ .

Ducks breed in the prairie pothole region in May and begin the fall flight south in September, which is also the start of hunting season. The fall flight consists of the fraction  $s_1$  of May breeding ducks ( $D_t$ ) that survive to September, plus their offspring that also survive to September. The latter is given by the recruitment (production) function  $g(D_t, W_t)$ , where  $\partial g/\partial D_t > 0$ ,  $\partial^2 g/\partial D_t^2 \leq 0$ ,  $\partial g/\partial W_t > 0$ ,  $\partial^2 g/\partial W_t^2 \leq 0$ . Equation (2.2) is maximized subject to the following bioeconomic constraints:

$$D_{t+1} = s_2 [s_1 D_t + g(D_t, W_t) - \pi h_t], \quad (2.3)$$

$$D_t, h_t, W_t \geq 0; \text{ and } D_0 > 0, W_0 > 0 \text{ given} \quad (2.4)$$

where  $D_{t+1}$  is the number of mature ducks returning to the prairie pothole breeding grounds in year  $t+1$ ,  $s_1$  is the fraction of May breeders surviving to September,  $s_2$  is the fraction of mature ducks that are not killed by hunters and survive to return to the breeding grounds in year  $t+1$ , and  $\pi > 1$  accounts for the loss of ducks that are killed or maimed by hunters but not collected or reported. Conditions (2.4) are non-negativity requirements and initial conditions regarding the numbers of ducks and ponds.

Applying Bellman's principle of optimality leads to the following recurrence relation known as Bellman's equation (Léonard and Van Long 1992, pp.174-176):<sup>5</sup>

$$V_t(h_t, D_t, W_t, \lambda_{t+1}) = \underset{h_t, W_t}{\text{Maximize}} \{ [v(h_t, y_t, Z_t) + \alpha D_t + B(W_t) - C(W_t)] + \rho V_{t+1}(D_{t+1}) \}. \quad (2.5)$$

where  $V_t$  is a value function and  $\lambda_t = \partial V_t / \partial D_t$  is the shadow price of an additional duck. Equation (2.5) can be solved using backward recursion based on the assumption that the social planner or authority behaves optimally in the future so that the value at time  $t+1$ ,  $V_{t+1}$ , is the best one can do.<sup>6</sup> The first-order conditions are found by setting  $\partial V_t / \partial h_t = 0$  and  $\partial V_t / \partial W_t = 0$ , and then differentiating both sides of (2.5) by the state variables  $D_t$  (recalling that  $D_{t+1}$  is a function of  $D_t$ ).

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

$$\partial V_t / \partial h_t = \partial v / \partial h_t - \rho \lambda_{t+1} s_2 \pi = 0 \quad (2.6)$$

$$\partial V_t / \partial W_t = B'(W_t) - c + \rho \lambda_{t+1} s_2 \partial g / \partial W_t = 0 \quad (2.7)$$

$$\partial V_t / \partial D_t = \lambda_t = \alpha + \rho \lambda_{t+1} s_2 (s_1 + \partial g / \partial D_t) \quad (2.8)$$

where  $c = dC/dW_t$  is the annual opportunity cost of providing an additional pond.<sup>7</sup> Additionally, the state equation (2.3) must be satisfied; the sufficient conditions for a

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<sup>5</sup> Decisions are made starting in period 1 (December 31), given start values at the beginning of period 1. This applies to models in Chapters 3 and 4 as well.

<sup>6</sup> The backward recursive approach of dynamic programming best lends itself to numerical solutions. In that case,  $T$  must be finite and the value  $V_T(D_T)$  must be specified.

<sup>7</sup> The marginal cost of providing an additional pond need not be constant, but could be a function of the number of ponds, so that we would write  $c(W_t) = dC/dW_t$ .

maximum are guaranteed by Bellman's optimality principle with  $\lim_{t \rightarrow \infty} \lambda_t \rho^t D_t = 0$ .<sup>8</sup> Equations (2.6) and (2.7) constitute a maximum principle, while equation (2.8) is the co-state equation.

From maximum principle (2.6), we find that  $(1/\pi) \partial v / \partial h_t = \rho \lambda_{t+1} s_2$ , which says that hunting should continue until the value of the marginal duck that is harvested (adjusted for the fact that not all birds killed are recovered) equals the user cost of taking that bird (which equals its discounted shadow value adjusted for the fact that not all unharvested ducks survive to breed the following spring). Similarly, from maximum principle (2.7), we find:  $c = B'(W_t) + \rho \lambda_{t+1} s_2 \partial g / \partial W_t$ . The left-hand side of this expression is the current cost of an additional pond, which is simply the cost of establishing or protecting it. The right-hand side is the marginal benefit of an additional pond, which consists of the sum of two terms. The first term constitutes the current marginal ecosystem service and other amenity values of the pond,  $B'(W_t)$ . This term is absent from the H&B model as they do not consider nonmarket values of wetlands. The second term is the marginal value of an additional wetland in the production of ducks that return to the breeding ground next year. Note that the shadow value of next year's duck is adjusted by the discount factor  $\rho$  and the mortality risk.

The final condition (2.8) can best be interpreted by re-writing it as  $\lambda_t - \alpha = \rho \lambda_{t+1} s_2 (s_1 + \partial g / \partial D_t)$ . In the absence of the amenity term  $\alpha$ , the discounted future (shadow) value of allowing a duck to escape (adjusted for mortality and the marginal growth in duck

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<sup>8</sup> Notice also that functions  $v(\cdot)$  and  $g(\cdot)$  are taken to be non-changing over time. Further, the last condition says that either it is optimal to drive the duck population to zero at some future time or the present shadow value of an additional duck is zero.

population) must equal the current (shadow) value of harvesting that duck,  $\lambda_t$ . From the perspective of the planner, however, the shadow value of the marginal duck to hunters needs to be reduced by  $\alpha$ , because the planner needs to take into account the non-use value that a duck provides citizens. This is done by raising the population of waterfowl over that in the case where ducks only have value to hunters – the case considered by H&B. Compared to the hunters-only case, more ducks are allowed to escape to the next year to satisfy both the need to make more birds available to hunters in the future and the non-use value ducks provide.

Substitute  $\rho \lambda_{t+1} s_2$  from (2.6) and from (2.7) into (2.8) to get the following expressions for the current shadow price of waterfowl:

$$\lambda_t = \alpha + \frac{1}{\pi} \left( s_1 + \frac{\partial g}{\partial D_t} \right) \frac{\partial v_t}{\partial h_t} \quad \text{and} \quad (2.9)$$

$$\lambda_t = \alpha + \frac{[c - B'(W)] \left( s_1 + \frac{\partial g}{\partial D_t} \right)}{\frac{\partial g}{\partial W_t}}. \quad (2.10)$$

Setting (2.9) equal to (2.10), and rearranging, gives a relationship similar to (2.7), but one that more clearly spells out the relationship between ponds and the value of waterfowl:

$$c = \frac{1}{\pi} \frac{\partial v}{\partial h_t} \frac{\partial g}{\partial W_t} + B'(W). \quad (2.11)$$

The left-hand side of (2.11) is the (marginal) social cost of providing an additional pond, while the right-hand side is the value of the additional pond in the production of ducks for hunters plus the ecosystem service and non-use benefits it provides.

A steady-state solution is found by letting  $\lambda_{t+1}=\lambda_t$  and  $D_{t+1}=D_t$ ,  $\forall t$ . We then find the following three steady-state conditions from equations (2.6), (2.7), (2.8) and (2.3):

$$B'(W) + \frac{1}{\pi} \frac{\partial v}{\partial h} \frac{\partial g}{\partial W} = c, \quad (2.12)$$

$$\left( s_1 s_2 + s_2 \frac{\partial g}{\partial D} - 1 \right) + \frac{\pi s_2}{\partial v / \partial h} \alpha = r, \text{ and} \quad (2.13)$$

$$(1 - s_1 s_2) D = s_2 (g(D, W) - \pi h). \quad (2.14)$$

Once functional forms and associated parameters are chosen, equations (2.12), (2.13) and (2.14) can be solved simultaneously for the optimal waterfowl population and optimal decisions concerning hunters' duck harvests and number of ponds that maximize the social planner's wellbeing. To find the steady-state solutions if the non-use values of wetlands and ducks are ignored, the terms  $B'(W)$  in equation (2.12) and  $\alpha$  in (2.13) would need to be set to zero. This would provide optimal values of our variables in H&B's case where the focus is solely on hunters' benefits.

## Model Calibration

An important component of bioeconomic modeling is the specification and estimation of the objective function and the state equations (or equations of motion). Given lack of information about the demand function for duck hunting, we adapt the equation estimated by Brown and Hammack (1973) using H&B's (1974, p.29) mean values of the regressors, but adjusting mean hunters' incomes and expenditures on duck hunting by the U.S. CPI. The resulting valuation function is then  $v(h) = 1.62 h^{0.409}$ . This function gives values of \$2.15 for the killing of two ducks and \$3.37 for six ducks, while

the marginal value of the sixth duck is \$0.24; these values are clearly several orders of magnitude too small. H&B also multiplied this relation by the number of hunters.

In 2007, a total of 815,300 duck hunters in the Mississippi, Central and Pacific flyways spent an average of 7.2 days in the field and bagged 15.7 ducks; in 2008, 802,400 hunters harvested an average of 14.8 ducks and spent 7.1 days on the activity (Table 2.1).<sup>9</sup> Using 1972-2008 data for Alberta, harvests averaged 12.8 ducks per hunter annually. Based on 20 studies, Loomis (2000) finds an average value of a wilderness recreation day to be \$39.61 in 1996 US dollars, or \$53.83 in 2008 after adjusting for inflation. Assuming duck hunters spend an average of 7 days in the field and harvest 14.5 birds, each bird is then worth approximately \$26. Multiply this value by an average harvest of 12.3 million ducks over 2007 and 2008 in the Mississippi, Central and Pacific flyways gives a total benefit of \$319.8 million. Assuming the parameter on harvest is the same as that in Hammack and Brown (0.409), we find that  $v(h) = 114.580 h^{0.409}$  with  $v(h)$  and  $h$  measured in millions. For sensitivity analysis, we assume the parameter value on harvest is 0.6, and calculate  $v(h) = 70.947 h^{0.6}$ .

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<sup>9</sup> We focus on U.S. hunters because the U.S. Fish and Wildlife Service (2010) contribute to the collection of data in Canada and the U.S. contributes to wetlands protection in Canada under NAWMP.

**Table 2.1: Duck Hunting and Harvest Data, United States, 2007 and 2008**

Flyway	Year	Harvest	Hunters	Harvest per hunter	Days afield	Days per hunter
Mississippi	2007	6,719,700	474,400	14.2	3,479,100	7.3
	2008	6,522,900	466,400	14.0	3,410,000	7.3
Central	2007	2,666,000	193,400	13.8	1,127,400	5.8
	2008	2,086,700	178,300	11.7	946,100	5.3
Pacific	2007	3,441,000	147,500	23.3	1,269,900	8.6
	2008	3,300,600	157,700	20.9	1,303,300	8.3
U.S. Totals	2007	14,578,900	995,700	14.6	6,978,400	7.0
	2008	13,723,200	980,500	14.0	6,686,400	6.8

Source: U.S. Fish and Wildlife Service (2010)

Woodward and Wui (2001), and Brander, Florax and Vermaat (2006), used meta-regression analysis to determine the ecosystem service values of wetlands. The average wetland value in Brander et al. was \$2,800 per hectare, but the median value was only \$150, indicating that the distribution of values is skewed with a long tail of high values. The median North American wetland value is somewhat higher than that in other locations (included in the meta analyses), but much less than that for Europe, while wetlands of the northern grain belt are likely to be less valuable than those elsewhere in North America. In Woodward and Wui, the average value of wetland services for benefit transfer purposes in Canada is \$137 per acre, while the minimum value is \$51 per acre. Finally, Cortus et al. (2010) calculate the net benefits of wetland retention in Saskatchewan by adapting the gross public benefits of wetland retention from Belcher et al. (2001). Their ‘best estimate’ of public benefits of wetlands is \$81.55 per hectare, while the low estimate is \$39.62. In the current study, we use the low value of wetlands benefits as our base case but conduct sensitivity analysis using the best estimate.

In the above studies, benefits are measured in hectares or acres, and are not on a pond basis. Cowardin, Shaffer and Arnold (1995) find that 78% of wetlands in the northern U.S. Great Plains cover 0.41 ha or less. Assuming an exponential distribution, we calculate the average pond to have an area of 0.27 ha.<sup>10</sup> Then the base case value is \$10.69 per pond and the higher estimate for sensitivity purposes is \$22.01 per pond, or assumed constant marginal benefits of \$10 and \$22 per pond for simulation purposes.

The annual cost of restoring a wetland (a pond) is given by the (marginal) opportunity cost of retaining the wetland plus the annualized cost of restoring it. As we are interested in finding the socially optimal level of wetlands in the PPR, and that this requires restoring wetlands, both costs must be considered in the model. The annual net opportunity cost of retaining wetlands equals the reduction in the value of cultivated land or land in its best alternative use, while restoration of wetlands results in a one-time cost that needs to be annualized using the discount rate (as described below).

The net opportunity costs of protecting or restoring wetlands equals the reduction in the value of cultivated land or land in its best alternative use. In cases where flooding is common, or where wetlands are permanent, the cost might be zero. Further, net returns to agricultural land vary considerably from year to year, from one crop to another, and across the prairie pothole region. Cortus et al. (2010) use a farm level simulation model to derive the net opportunity costs of retaining wetlands in the PPR, determining it to be between \$28 and \$41 per hectare, or between \$8 and \$11 per pond.

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<sup>10</sup> The cumulative probability function is:  $\text{Prob}(x < X) = 1 - e^{-3.693x}$ . H&B (1974, p.69) indicate that the average size of a pond in the Prairie pothole region was determined to be 0.85 acres or 0.34 hectares.

Information on the costs of restoring wetlands is available from Hansen (2009), although it is based on the USDA's Wetlands Restoration Program. For the prairie pothole area, average restoration costs rose from \$545 per acre (\$1,346 per ha) for the 25<sup>th</sup> percentile to \$1,160 (\$3,132/ha) for the 50<sup>th</sup> percentile, and \$1,953 (\$4,824/ha) for the 75<sup>th</sup> percentile (in 2007 US dollars). This translates into costs of about \$360, \$840 and \$1,300 per pond for the 25<sup>th</sup>, 50<sup>th</sup> and 75<sup>th</sup> percentiles, respectively. It should be noted that, under the USDA program, restored wetlands exclude those that might be considered 'permanent' – ones landowners have never made the effort to convert to cropland, and are unlikely to be converted in the foreseeable future. In the PPR, the least number of ponds during the period 1955-2009 was rarely below 2 million and then only in years, such as 2002, when precipitation was particularly low (Figure 2.5). The cost to the authority of providing this minimum level of wetlands is likely close to zero.

We assume that restoration costs are zero for the first 2.0 million ponds and that, for convenience, the marginal cost of protecting any pond beyond this amount is constant. The restoration costs of \$360 to \$1300 per pond are one-time costs which must be converted to annual costs. For example, a wetland may be restored and the authority might then purchase a 30-year easement on the larger property (Hansen 2009). In that case, the annualized restoration cost would be \$12 to \$44 per pond.

Summing the annualized restoration cost and annual opportunity costs, we find that costs range broadly from \$20 to \$55 per pond. We use a conservative approach and assume the overall annual net (marginal opportunity) cost of keeping a wetland is \$55 per pond, although we employ sensitivity analysis with costs ranging from \$35 to \$65.

B&H (1973), H&B (1974) and Brown et al. (1976) use two functional forms for the waterfowl production function – a double-logarithmic form (or Cobb-Douglas) and a Beverton-Holt production function. The respective functional forms are:

$$g(D_t, W_t) = AD_t^{\varphi_1} W_t^{\varphi_2} \text{ and} \quad (2.15a)$$

$$g(D_t, W_t) = \left( \frac{d_0}{D_t} + \frac{1}{d_1 W_t^{d_2}} \right)^{-1}. \quad (2.15b)$$

As the number of breeding ducks grows to infinity, the number of offspring grows indefinitely large in the case of the Cobb-Douglas production function, but is bounded by the available habitat (the ecosystem carrying capacity) in the case of the Beverton-Holt model – the limit approaches  $d_1 W_t^{d_2}$  asymptotically. We also examine a standard logistic growth function (which is now commonly used in bioeconomic models):

$$g(D_t, W_t) = \gamma D_t \left( 1 - \frac{D_t}{g W_t^b} \right) \quad (2.15c)$$

where  $\gamma$  is the intrinsic growth rate and  $g W_t^b$  is the carrying capacity of the prairie pothole ecosystem.<sup>11</sup>

We have data on breeding ducks and immature offspring, and on wetlands (May pond counts), for the prairie pothole region of southern Alberta, Saskatchewan and Manitoba, namely, the U.S. Fish and Wildlife Service's (2010) strata 26 through 40, over the period 1955 to 2009. We also have data on July ponds for the period 1955-2003, U.S. hunters' duck harvests for the Central flyway for the period 1961-2008, and Canadian

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<sup>11</sup> In equations (13),  $\varphi_1$ ,  $\varphi_2$ ,  $d_0$ ,  $d_1$ ,  $d_2$ ,  $\gamma$ ,  $g$  and  $b$  are parameters to be estimated.

harvests of ducks for the period 1969-2008. We use this data to estimate each of the relationships in (2.15). The first two production functions were used by H&B, while the latter is employed here. Similar to H&B, we find that May ponds provide a better statistical fit than July ponds, so we present only the regression results with May ponds.

The nonlinear least squares regression results are as follows:<sup>12</sup>

$$g(D_t, W_t) = 0.880 D^{0.924} W^{0.608}, R^2 = 0.6715 \quad (2.16a)$$

(0.32) (4.73) (3.59)

$$g(D_t, W_t) = \left( \frac{0.430}{D} + \frac{1}{5.668W^{2.024}} \right)^{-1}, R^2 = 0.6715 \quad (2.16b)$$

(4.88) (1.79) (2.85)

$$g(D_t, W_t) = 2.89D \left( 1 - \frac{D}{12.29W^{0.91}} \right), R^2 = 0.50 \quad (2.16c)$$

(8.73) (4.20) (4.25)

Unlike H&B's (1974, p.49) regression, our Cobb-Douglas production function (2.16a) does not exhibit constant returns to scale as the sum of the estimated coefficients exceeds 1.0 (0.924+0.608=1.532), indicating increasing returns to scale production. If we apply the estimated parameters of Cobb-Douglas equation (2.16a), we find that increases in the costs of restoring wetlands are offset in the steady state by unbounded increases in optimal breeding populations, an unrealistic result. For the estimated parameters of the Beverton-Holt model in (2.16b), the dynamic model turns out to be highly unstable, which is not unusual in the case of the Beverton-Holt model, as noted by van Kooten and

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<sup>12</sup> The t-statistics are in parenthesis below the expression in which the estimated coefficient is found and are based on Newey-West HAC standard errors.

Bulte (2000, p.184). Although we could duplicate H&B's analysis with their original parameter estimates, we could not duplicate their analysis when we employed their production functions but with parameters estimated using up-to-date duck population and wetlands data. Therefore, we rely only on the estimated logistics growth function (2.16c) in the numerical analysis.

Finally, we employ H&B's (1974, p.50) values for intra-year survival rates for the period between breeding in May and the start of hunting season in September ( $s_1$ ) and the period after hunting season until breeding begins ( $s_2$ ). Brown et al. (1976) assume 5% of duck kills are not reported, and we use this factor to account for underreporting of bird kills by hunters. Loomis and White (1996) report non-use values for several endangered bird species, which are quite large for some species such as Whooping Crane. Ducks and geese tend to be plentiful, so their value to bird watchers and other viewers tends to be smaller. Therefore, we use a very low value for the amenity value of ducks. This value is lower than the values of endangered bird species reported by Loomis and White.

## **Numerical Simulation Results**

We determine the steady-state solutions by solving the system of equations (2.12), (2.13) and (2.14) for the case where non-use values are not taken into account (only hunter values are considered), and the steady-state solutions when non-use values of wetlands and ducks are included. A summary of the functions and parameter values used in the simulations is provided in Table 2.2. Table 2.3 presents steady state values of ducks, harvests and wetlands. These results correspond to the base case values provided in Table 2.2.

**Table 2.2: Model Functions and Parameters used in the Simulations**

Item	Base Case	Sensitivity
Marginal hunter benefit function	$\partial v/\partial h = 46.863 h^{-0.6}$	$\partial v/\partial h = 42.568 h^{-0.4}$
Marginal product of wetlands in duck production	$\partial g/\partial W = 0.214D^2W^{-1.91}$	$\partial g/\partial W = 0.214D^2W^{-1.91}$
Marginal product of breeding ducks	$\partial g/\partial D = 2.89-0.470DW^{0.91}$	$\partial g/\partial D = 2.89-0.470DW^{0.91}$
Intra-year duck survival rates	$s_1 = 0.95$ $s_2 = 0.80$	$s_1 = 0.95$ $s_2 = 0.85$
Marginal cost of protecting wetlands	$c = C'(W) = \$55$	$c = C'(W) = \$65, 45, 35$
Marginal amenity value of wetlands	$B'(W) = \$10$	$B'(W) = \$20, 30$
Marginal non-hunting value of a duck	$\alpha = \$1$	$\alpha = \$2, 3$
Adjustment for underreporting of kills	$\pi = 1.35$	$\pi = 1.35$

In Table 2.3, we compare the case when non-hunter (non-use) amenity values are not taken into account (the H&B situation) and when they are – the ‘no amenity value’ versus ‘amenity value’ cases. In the base case amenity value scenario, optimal wetlands, harvests and ducks are all higher than historic levels. Wetlands should be about 17 percent higher, which is consistent with Hammack and Brown, while the duck population and harvests should be about 50% and 60% higher than historic levels, respectively. Because we employ a logistics growth function (2.16c), the proportion of ducks and harvests to wetlands is determined to be higher than historically.

**Table 2.3: Historic and Steady State Values of Ponds, Ducks and Harvests, Various Net Costs of Wetlands Restoration (millions)**

Item	Ponds ( $W$ )	Ducks ( $D$ )	Harvests ( $h$ )
Historic values <sup>a</sup>	3.5	13.5	12.3
		<i>Base Case</i>	
No amenity value	2.6	12.8	12.6
Amenity value	4.1	20.3	19.6
		<i>Cost=\$45; B'(W)=\$10<sup>b</sup></i>	
No Amenity value	3.5	17.0	16.8
Amenity value	6.3	30.6	29.0
		<i>Cost=\$35; B'(W)=\$10<sup>b</sup></i>	
No amenity value	5.2	24.4	24.1
Amenity value	11.6	54.3	50.0
		<i>Cost=\$65; B'(W)=\$10<sup>b</sup></i>	
No amenity value	1.96	9.9	10.0
Amenity value	2.9	14.8	14.3

<sup>a</sup> Source: Ponds and ducks are for Canada's prairie region and based on the average of 1955-2008 data from the U.S. Fish and Wildlife Service (2010), while harvest is the average of 2007-2008 U.S. harvest for the Pacific, Mississippi and Central flyways (average total U.S. duck harvest was 14.1 million). There exists a mismatch in terms of the regions used for reporting of ponds versus waterfowl population data and harvest data.

<sup>b</sup> Cost refers to net annualized costs of restoring a pond plus the annual opportunity cost, while  $B'(W)$  is the nonmarket (ecosystem service plus other amenity) benefit of an additional pond.

For a basic model similar to that of Brown and Hammack (1973) but with a cost of \$55 per pond, optimal wetlands, ducks and harvests are projected to be 2.6, 12.8 and 12.6 million, respectively. The values for ponds and ducks are smaller than historical values, which is contrary to H&B's (1973) finding. However, as one decreases the cost of restoring and retaining ponds, the optimal values of all variables increase significantly (Table 3). Indeed, when we use a cost of \$12 per pond, we confirm H&B's result.

When the value of wetland ecosystem services and other amenities is included, the socially optimal level of wetlands increases – increasing the marginal benefit of a pond should increase the number of ponds, which in turns leads to an increase in ducks

and harvests as a result of increased breeding habitat. Then, increasing the in-situ value of ducks ( $\alpha$ ) will decrease the shadow value of the marginal duck to hunters, indicating that the planner needs to raise the population of waterfowl over that in the model where ducks only had value to hunters.

In addition to the actual values obtained in Table 2.3, ratios of ducks per pond and harvests per pond can easily be calculated. For May pond data, the historical levels are 3.85 ducks and 3.54 harvests per pond. In the current model under the base case 'amenity value' scenario, the optimal levels of ducks and harvests to ponds are 4.98 and 4.79, respectively. Thus, given the number of wetlands, historic levels of both waterfowl and harvests are too low from a social planner's perspective. This result could be an artifact of the logistics growth model, but it could also be that more should be done to provide dense nesting cover for breeding waterfowl, thereby increasing wetlands productivity.

Our estimate of \$55 as the net annual cost of restoring and retaining ponds might be considered high, and, from our review of the literature, it is quite possible that the net costs of ponds could be lower. Thus, we estimate the model using costs of \$45 and \$35 per pond and, for illustrative purposes, \$65. However, given that  $B'(W)=\$10$ , the net effective annual social cost of restoring a marginal pond is reduced by \$10 as indicated in Table 3 where the results are also found. Further, an increase in the non-use value of ducks will likely raise the socially optimal levels of wetlands, ducks and harvests; therefore, we consider values for  $\alpha$  of \$2 and \$3 per duck in Table 2.4.

**Table 2.4: Sensitivity of Optimal Ponds, Ducks and Harvests to the Non-Use Value of Ducks, Selected Costs of Restoring and Retaining Wetlands (millions)**

Item	Ponds ( $W$ )	Ducks ( $D$ )	Harvests ( $h$ )
Historic values	3.5	13.5	12.3
Value of a duck <sup>a</sup>	<i>Net Cost of Ponds = \$55<sup>b</sup></i>		
$\alpha=1$	4.1	20.3	19.6
$\alpha=2$	4.9	25.4	22.9
$\alpha=3$	6.1	33.1	27.6
	<i>Net Cost of Ponds = \$45<sup>b</sup></i>		
$\alpha=1$	6.3	30.6	29.0
$\alpha=2$	8.0	41.0	35.6
$\alpha=3$	11.1	60.0	46.1

<sup>a</sup> Base case non-use value of a duck is  $\alpha=1$ .

<sup>b</sup> Net cost refers to net annualized costs of restoring a pond plus the annual opportunity cost. From this the marginal non-market benefit of wetlands,  $B'(W)=\$10$ , would be subtracted.

Results are sensitive to the values assumed for the net costs of ponds and the non-use value of waterfowl. If we reduce the cost of ponds and/or increase their marginal non-market benefit by \$20 per pond, wetlands will increase nearly threefold in the ‘amenity value’ scenario (Table 2.3). Further, as indicated in Table 2.4, if we increase the non-use value of ducks from \$1 to \$2, the optimal value of wetlands to retain increases by an additional 19.5% to 27.0%, depending on which value of net effective costs is used (\$55 or \$45). The results are clearly sensitive to both the net costs of ponds and amenity values of wetlands and ducks.

Finally, different specifications of the waterfowl production and duck valuation functions will impact the results. A Cobb-Douglas functional form for duck production results in increasing returns to scale, as discussed previously. Although results are not shown, this leads to significantly higher steady-state waterfowl populations and harvest

levels in the model than could realistically occur. Even changing the parameters on the current duck valuation function, such that  $\partial v/\partial h = 42.568 h^{-0.4}$ , will result in values of wetlands, ducks and harvests than are significantly higher than those in Table 2.3. The impact of functional form for hunters can be seen in Table 2.5, where the base case is compared to that with different parameters for the duck valuation function.

**Table 2.5: Sensitivity to Duck Valuation Functional Form**

Item	Ponds ( <i>W</i> )	Ducks ( <i>D</i> )	Harvests ( <i>h</i> )
	(millions)		
Historic Value	3.5	13.5	12.3
	$\partial v/\partial h = 46.863 h^{-0.6}$		
No Amenity Value	2.55	12.8	12.6
Amenity Value	4.1	20.3	19.6
	$\partial v/\partial h = 42.568 h^{-0.4}$		
No Amenity Value	6.4	29.3	29.0
Amenity Value	12.0	54.1	52.3

<sup>a</sup> Using base case values. Optimal values for ducks and ponds in Table 3 are calibrated to the Canadian prairie pothole region, because the production function was estimated using prairie pothole duck and pond data. The harvest is the combined kill in the U.S. Mississippi, Central and Pacific regions, while the duck valuation function was based on a survey conducted in the Pacific region. In order to calibrate the duck valuation function to other flyways, it is assumed that people's preferences are similar across regions.

## Concluding Observations

Gardner Brown and Judd Hammack were the first to employ bioeconomic modelling in the context of wildlife habitat protection, demonstrating that, on the basis of duck hunting values alone, the socially optimal level of wetlands protection was below the existing level. In coming to this conclusion, these researchers ignored the ecosystem service and other amenity benefits associated with wetlands as well as the benefits people get from viewing waterfowl. In this study, we sought first to duplicate their results and

then extend their analysis to include nonmarket in-situ values of waterfowl and wetlands. While we could duplicate their results for the parameters they had estimated, we found that using updated data led to an estimated Cobb-Douglas production function with increasing returns to scale in wetlands and breeding ducks; this, in turn, resulted in unrealistic model results. For the parameters of the Beverton-Holt model of equation (16b), the dynamic model turned out to be highly unstable. For these reasons, we used a logistic production function that is commonly used in bioeconomic wildlife models (van Kooten and Bulte 2000).

In our analysis, we examined a model based only on hunting values (B&H's model but modified) and one that was expanded to include the non-use value of waterfowl and the ecosystem service and other nonmarket values of wetlands. Results were clearly very sensitive to functional form and parameter values; yet, there are some key policy conclusions, the first of which reinforces the earlier findings by B&H (1973) and H&B (1974). From the social planner's point of view, the optimal management of waterfowl is such that wetlands, ducks and harvests should all be higher than historically observed levels. Second, it is important to add amenity values as their inclusion significantly increases the level of wetlands, ducks and harvests relative to a model that does not include these values. Third, based on the results in this model, the level of ducks and harvest relative to the level of May ponds should be higher than historically observed levels. Brown and Hammack's (1973) original conclusion was reinforced – the numbers of wetlands protected in the Canadian prairie pothole region is less than what is socially optimal. Therefore, it is socially optimal to provide incentives to increase the area of wetlands in the prairie pothole region.

In our analysis, we relied exclusively on sensitivity analysis to address randomness, recognizing that this may not lead to quite the same outcome as one in which explicit account is taken of uncertainty in making decisions. That is, optimal management strategies obtained from sensitivity analysis are not necessarily optimal from the perspective of a planner who considers randomness in the decision calculus. Future research needs to take uncertainty into explicit account, including uncertainty related to future climate change. In addition to uncertainty, it is important that future research also consider spatial aspects because migratory waterfowl may well choose to breed elsewhere in the prairie pothole region, or even in the boreal forest, when wetlands in a particular sub-region are insufficient (due perhaps to climate change). This reduces the value of wetlands in duck production, but not likely in terms of their ecosystem service and other non-use values.

## **Chapter 3**

# **The Effect of Climate Change on Optimal Wetlands and Waterfowl Management in Western Canada**

### **Introduction**

Climate change is expected to increase drought in the southern parts of the Canadian Prairie provinces of Alberta, Saskatchewan and Manitoba, also known as the prairie pothole region, because of increased temperatures and changes to patterns of precipitation (Johnson et al. 2005, p.864). Conditions in the 21<sup>st</sup> century are expected to be substantially drier than during the past century, perhaps closer to what they were in the mid 1800s when explorers found much of the region to be too dry to warrant cropping (The University of Calgary 1997). Drier conditions will have a major impact on the prairie pothole region (PPR) – North America’s ‘duck factory.’ A drier climate will reduce wetlands, which will have an adverse impact on agricultural ecosystems and the region’s ability to produce waterfowl, as seen from the correlation between wetlands and breeding duck populations in Figure 3.1. Drier conditions will simply mean that the region will not be able to support historically observed levels of migratory waterfowl.

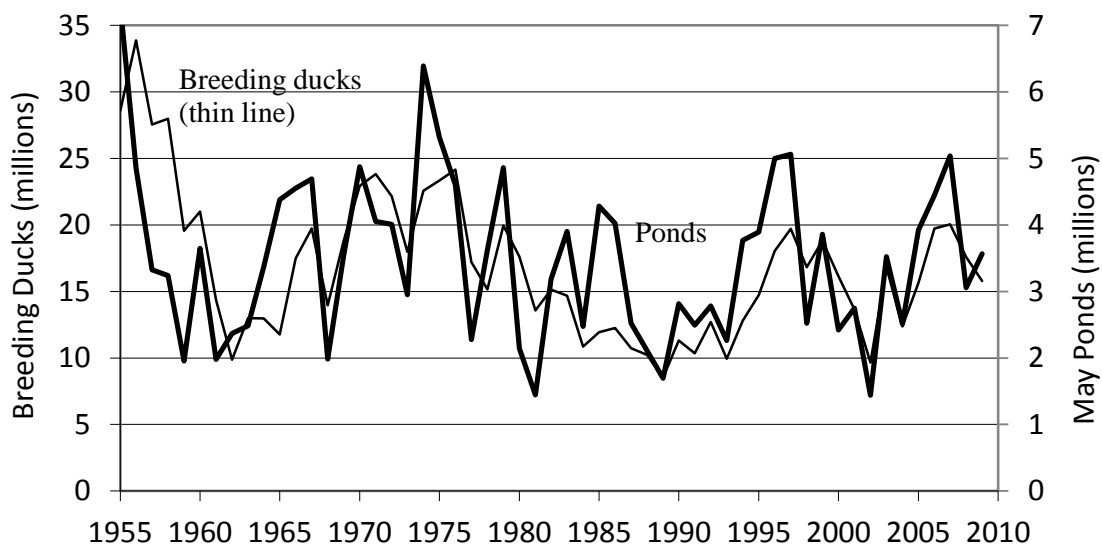


Figure 3.1: Relationship between Wetlands and Waterfowl in Canada's Grain Belt, 1955-2009

The International Panel on Climate Change (IPCC) predicts that surface temperatures around the globe could rise by between 1.1 and 6.4 degrees Celsius by 2100 (Solomon et al. 2007, p.13), while regional climate models predict that temperatures could rise by 1.8°C to 4°C in the prairie pothole region (Johnson et al. 2010). Future precipitation patterns are more difficult to predict. Johnson et al. (2005) point out that changes in average annual precipitation during the next 100 years may vary between a decrease of 20% and an increase of 20%, while other analysts predict changes between a decline of 5% and an increase of 10% (Solomon et al. 2007). Further, both Ojima et al. (2002) and Johnson et al. (2004) indicate that climate change will likely increase droughts and torrential rains.

Several studies have used multiple regression models to estimate the causal effect of climate change on wetlands. Using the Palmer Drought Index (PDI), Sorenson et al. (1998) estimate the effect of climate change on wetlands in the north central United

States, while Larson (1995) employs temperature and precipitation data to estimate the effect of climate on wetlands in the U.S. and Canada. In this study, therefore, we use a multiple regression framework and data on drought, temperature and precipitation to estimate the impact of climate change on wetlands in Canada's prairie pothole region, which lies above the above the Canada-U.S border (Figure 3.2).



*Figure 3.2: The Prairie Pothole Region of North America*  
Source: Northern Prairie Wildlife Research Centre

In the current research rather than using the PDI, we rely on the Standardized Precipitation Index (SPI), which is a popular drought index based solely on precipitation. Bethke et al. (1995) and Adams (1988) argue that the best indicator of wetlands in the Canadian PPR is precipitation in the previous year. This correlation is verified in Figure 3.3, where wetlands (as measured by pond numbers) and a one-year lag of precipitation are plotted for the PPR. Further, the drought that was caused when precipitation fell in 2001 to 40% of its historical average was followed in 2002 by the lowest number of

wetlands in recent history. Given the observed effect of precipitation on wetlands in the PPR, the SPI variable likely captures the relationship well. For robustness, we also used data on temperatures and precipitation, and compare results using both models.

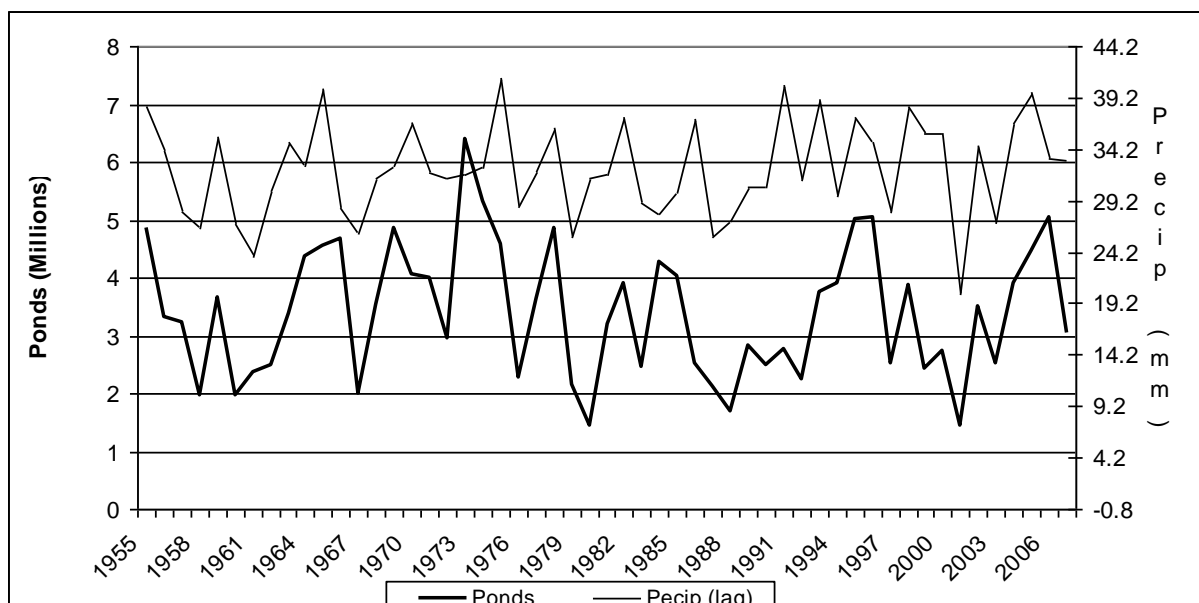


Figure 3.3: May ponds and Lagged Precipitation in the Canadian PPR

Another contribution of the current study is that, in addition to estimating the effect of climate change on wetlands, we use a bioeconomic model to find the optimal level of wetlands and duck harvests. The bioeconomic model is based on a model by van Kooten et al. (2011) (the model presented in Chapter 2) that extends an earlier model of migratory waterfowl and wetlands due to Gardner Brown and Judd Hammack (Hammack and Brown 1974; Brown and Hammack 1973; Brown, Hammack and Tillman 1976). Brown and Hammack's waterfowl management model focused solely on the consumptive value of waterfowl. But, in addition to their (consumptive) use value to hunters, waterfowl also have non-use value while wetlands have a variety of use and non-use values outside of their role in producing waterfowl. For instance, wetlands filter

agricultural and other pollutants, provide water for livestock and wildlife, contribute to visual and recreational amenities, and store greenhouse gases. Van Kooten et al. include amenity values of waterfowl and wetlands, but do not take climate into account.

The objectives in this study are to (1) estimate the causal effect of climate indicators on wetlands, (2) explore the impact that a changing climate might have on wetlands in Canada using results from linear regression models, and (3) estimate the impact of climate change on the optimal management of waterfowl and wetlands using a bioeconomic model. The current analysis ignores regional effects as well as the effect of biofuel policies on wetlands; however, such topics are explored in Chapters 4 and 5

The remainder of this paper is organized as follows. In the next section, we provide a brief overview of relevant literature. The two regression equations are then estimated, while the bioeconomic model is described and parameterized in the following section. In the fifth section, we first describe the climate scenarios and then employ the estimated regression equations to predict how wetlands might be expected to change under various climate scenarios. These projections are used in the logistics equation of the bioeconomic model to estimate socially optimal baseline (current climate) values of wetlands retention, duck populations and duck harvests, as well as optimal values that account for the effect of climate change on wetlands. We conclude by discussing the opportunities and challenges facing policymakers and directions for future research.

## **Literature**

We review literature that estimates the effect of direct climate change on wetlands and the abundance of ducks, focusing on the few studies that are most closely related to

the current study. A review of the literature on bioeconomic modeling of wetlands and waterfowl is not provided here, as this can be found in Chapter 2.

Larson (1995) estimates the effect of temperature and precipitation on wetlands using linear multiple regression analysis. Specifically, for the Canadian grasslands (PPR), she finds that the percentage of basins filled with water is a function of total precipitation that year, precipitation in the fall of the previous year, fall maximum average temperature, and the difference between April minimum and maximum average temperatures. For a 3°C increase in temperature, wetlands are projected to decline by 15 percent. Coupled with an increase (decrease) in precipitation of 10%, wetlands are projected to increase (decrease) by 2% (31%). We adopt Larson's approach but adjust the regression model on the basis of diagnostics tests. Further, we incorporate the regression results into a bioeconomic model of wetland and waterfowl retention.

Using PDI data for the north central U.S., Sorenson et al. (1998) estimate the effect of drought on wetlands. Upon regressing May ponds on average May PDI, they find  $R^2=0.72$ , indicating that the PDI explains a great deal of the variation in wetlands. The authors then estimate the effect of climate variables on PDI for various scenarios (increase of temperature between 1.5 and 4.0°C and changes of precipitation of -10% to +15%) and the corresponding effect on wetlands. Their results show that severe drought (PDI = -3.4) will decrease wetlands by 54 percent, whereas mild drought (-1.2) will decrease wetlands by 23 percent. For an increase in temperature of 1.5°C (2.5°C) coupled with an increase in precipitation of 7% (15%), wetlands decrease by 15% (15%). Consistent with previous studies (Larson 1995; Poiani and Johnson 1991), changes in wetlands are more sensitive to temperature changes than to changes in precipitation.

Johnson et al. (2005) use the WETSIM simulation model to estimate the spatial impact of wetlands in the following scenarios: an increase in temperature of a 3°C and no change in precipitation; a 3°C increase in temperature and a decrease in precipitation of 20%; and a 3°C increase and increase in precipitation of 20%. They find that drier conditions will severely decrease wetlands available for waterfowl habitat, but the effects are highly dependent on the specific future climate scenario. If precipitation is quite high (increase of 20%), the effect of increased temperature will be offset. If precipitation is constant or decreasing, wetlands will decrease and waterfowl habitat will be pushed to the north and east. Overall, arid regions of the U.S. Great Plains and Saskatchewan are extremely vulnerable to drier conditions.

Johnson et al. (2010) extend their earlier model to allow for heterogeneity in wetlands. Their simulation results suggest that all prairie wetlands will suffer due to warming; the order in which wetlands are susceptible increases from temporary wetlands to semi-permanent wetlands to seasonal ones. The results of the two studies by Johnson et al. (2005, 2010) are relevant to the current study. Our model predicts optimal values of wetlands and waterfowl due to climate change, while Johnson et al.'s spatial analysis sheds light on where the retention of wetlands might occur.

## **Multiple Regression Model**

### *Regression model*

We employ two specifications of the linear regression equation to estimate the impact of climate change on wetlands, because this provides some indication regarding the robustness of the model results. The first specification relies solely on the direct

impact of drought on wetlands, similar to Sorenson et al. (1998), with the SPI index used as the drought measure rather than the PDI. The second specification is similar to Larson (1995), with wetlands (pond numbers) regressed on the climate variables temperature and precipitation. Lagged values are considered for both SPI and precipitation, given that precipitation in previous years impacts wetlands (Figure 3.3). In each case, the final regression model is chosen on the basis of adjusted  $R^2$ , statistical significance of the regressors and other diagnostic tests. The final specifications of the alternative regression equations are as follows:

$$W_t = \beta_0 + \beta_1 SPI_{t-1} + \varepsilon_t, \quad (3.1)$$

$$W_t = \gamma_0 + \gamma_1 P_{t-1} + \gamma_2 T_{t-1} + \xi_t, \quad (3.2)$$

where  $W_t$  refers to wetlands (number of ponds) in period  $t$ ,  $SPI_{t-1}$  is the lagged value of SPI;  $P_{t-1}$  is the lagged value of precipitation;  $T_{t-1}$  is the lagged average annual maximum temperature; the  $\beta$ s and  $\gamma$ s are model parameters to be estimated; and  $\varepsilon_t$ , and  $\xi_t$  are assumed to be independent and identically distributed error terms that are normally distributed.

We test the null hypothesis of serial independence of the error terms, and use HAC estimates for the standard errors where necessary. We also conduct time series analysis of the data. Tests for unit roots in the data were conducted using Augmented Dickey Fuller (Dickey and Fuller 1979) and KPSS (Kwiatkowski et al. 1992) tests. In all cases, the variables are found to be stationary, which provides statistical confidence that we do not have spurious regressions.

### *Regression results*

The two regression equations were estimated using wetlands data from the annual May waterfowl breeding population and habitat surveys conducted by the United States Fish and Wildlife Service and the Canadian Wildlife Service. We use May pond counts in the southern prairie provinces, corresponding to U.S. Fish and Wildlife Service's strata 26-40 (which encompass the shaded region north of the U.S.-Canada border in Figure 3.2), for the period 1955-2007. Climate data were obtained from Environment Canada's Historical Weather and Climate Data series. 15 Climate stations were chosen and were distributed throughout Canada's PPR. Climate data consist of average annual maximum temperatures, annual spring and fall maximum temperatures, and total precipitation. SPI data were obtained from the North American Drought Monitor, using similar stations in the PPR. The SPI ranges from  $-4$  to  $+4$ ; negative values indicate dry conditions and positive values indicate wet conditions. A value of  $-1$  or less indicates drought, with the severity increasing as the SPI value falls.

Equations (3.1) and (3.2) are estimated by ordinary least squares:

$$W_t = 2.9 + 3.33SPI_{t-1}, \quad R^2=0.30, \text{ S.E}=0.95 \quad (3.3)$$

$$(26.28) \quad (4.84)$$

$$W_t = 3.138 + 0.0085P_{t-1} - 0.31T_{t-1}, \quad R^2=0.36, \text{ S.E}=0.91, \quad (3.4)$$

$$(1.83) \quad (4.07) \quad (-2.83)$$

where t-tests are provided in parentheses,  $W$  is measured in millions of May ponds,  $SPI$  is an index,  $P$  is in millimeters, and  $T$  is in degrees Celsius. Model (3.4) includes temperature and precipitation and leads to a higher  $R^2$  value, although neither (3.3) nor

(3.4) produce an  $R^2$  as high as that found by Larson (1995) or Sorenson et al. (1998). Nonetheless, the coefficients are statistically and practically significant, and all coefficients are of the expected sign. Lagged values of SPI, temperature and precipitation were more highly correlated with wetlands than the level values, and they produced a higher  $R^2$ .

We can also verify that the estimated models predict actual climate effects well, particularly equation (3.4). In 2001, the prairie pothole region experienced a large 40% decline in precipitation (relative to the historical average) and a higher than normal average temperature anomaly of 1.6°C. The regression models (3.3) and (3.4) predict that wetlands would decrease in 2002 (the year following the drought) to 2.1 million and 1.59 million, respectively, while actual ponds numbered 1.43 million in 2002. Therefore, we use results (3.3) and (3.4), coupled with potential climate change scenarios (described in section 5), to predict the impact of climate change on wetlands.

## **Bioeconomic Model**

### *Analytical model*

In this section, we present a bioeconomic model by van Kooten et al. (2011), or the model in Chapter 2 above, that estimates the optimal level of wetlands to retain. This model extends previous work by Hammack and Brown (1974) to include amenity values of wetlands and waterfowl. It is further modified here to incorporate climate factors.

Assume the social planner maximizes the following objective function:

$$\sum_{t=1}^T [v(h_t, y_t, Z_t) + \alpha D_t + B(W_t) - C(W_t)] \rho^t, \quad (3.5)$$

where  $v(h_t, y_t, Z_t)$  is a function of per capita income of duck hunters ( $y$ ), ducks harvested ( $h$ ) and demographic characteristics ( $Z$ ) that describes the benefits derived from duck hunting;  $B(W_t) - C(W_t)$  is the net benefit of providing  $W$  wetlands (measured in millions of ponds);  $\alpha$  is the non-use value of mature ducks returning to the breeding grounds in the spring ( $D_t$ ); and  $\rho = 1/(1+r)$  is the discount factor with  $r$  the discount rate. The length of the planning horizon is  $T$ .

The objective function is maximized subject to the ecological constraint that describes the change in ducks over time. Ducks in a given period are equal to a function of ducks in the previous period, the growth in (production of new) ducks, and the level of ducks that are harvested. Ducks breed in May and begin the fall flight south in September. Between then and their return to the breeding grounds the following year, the duck population is reduced by (legal and illegal) harvests and natural mortality. The dynamics of duck numbers is given by:

$$D_{t+1} = s_2 [s_1 D_t + g(D_t, W_t) - \pi h_t], \quad (3.6)$$

$$D_t, h_t, W_t \geq 0; \text{ and } D_0 > 0, W_0 > 0 \text{ given} \quad (3.7)$$

where  $D_{t+1}$  is the number of mature ducks returning to the prairie pothole breeding grounds in year  $t+1$ ;  $s_1$  is the fraction of May breeders surviving to September;  $s_2$  is the fraction of mature ducks that are not killed by hunters and survive to return to the breeding grounds in year  $t+1$  (so  $1-s_2$  is the natural mortality during this period); and  $\pi > 1$  accounts for the loss of ducks that are killed or maimed by hunters but not collected or reported. The number of offspring that are produced is given by the recruitment function

$g(D_t, W_t)$ , where  $\partial g/\partial D_t > 0$ ,  $\partial^2 g/\partial D_t^2 \leq 0$ ,  $\partial g/\partial W_t > 0$ ,  $\partial^2 g/\partial W_t^2 \leq 0$ . Conditions (3.7) are non-negativity requirements and initial numbers of ducks and ponds.

Objective function (3.5) is maximized subject to the constraints (3.6) and (3.7). Applying Bellman's principle of optimality leads to the following recurrence relation known as Bellman's equation (Léonard and Van Long 1992, pp.174-176):

$$V_t(h_t, D_t, W_t, \lambda_{t+1}) = \underset{h_t, W_t}{\text{Maximize}} \{ [v(h_t, y_t, Z_t) + \alpha D_t + B(W_t) - C(W_t)] + \rho V_{t+1}(D_{t+1}) \}. \quad (3.8)$$

where  $V_t$  is a value function and  $\lambda_t = \partial V_t/\partial D_t$  is the shadow price of an additional duck. Equation (3.8) can be solved using backward recursion based on the assumption that the social planner behaves optimally in the future so that the value at time  $t+1$ ,  $V_{t+1}$ , is the best one can do.<sup>13</sup> The first-order conditions are found by first setting  $\partial V_t/\partial h_t = 0$  and  $\partial V_t/\partial W_t = 0$ , and then differentiating both sides of (3.8) by the state variables  $D_t$  (recalling that  $D_{t+1}$  is a function of  $D_t$ ). Assuming an interior solution, the first-order conditions are:

$$\partial V_t/\partial h_t = \partial v/\partial h_t - \rho \lambda_{t+1} s_2 \pi = 0 \quad (3.9a)$$

$$\partial V_t/\partial W_t = B'(W_t) - c + \rho \lambda_{t+1} s_2 \partial g/\partial W_t = 0 \quad (3.9b)$$

$$\partial V_t/\partial D_t = \lambda_t = \alpha + \rho \lambda_{t+1} s_2 (s_1 + \partial g/\partial D_t) \quad (3.9c)$$

---

<sup>13</sup> The backward recursive approach of dynamic programming best lends itself to numerical solutions. In that case,  $T$  must be finite and the value  $V_T(D_T)$  must be specified.

where  $c = dC/dW_t$  is the annual cost of providing an additional pond in each period.<sup>14</sup> Additionally, the state equation (3.6) must be satisfied; the sufficient conditions for a maximum are guaranteed by Bellman's optimality principle with  $\lim_{t \rightarrow \infty} \lambda_t \rho^t D_t = 0$ .<sup>15</sup> Equations (3.9a) and (3.9b) constitute a maximum principle, while equation (3.9c) is the co-state equation. For a more detailed discussion of these first-order conditions, see van Kooten et al. (2011) (i.e. Chapter 2 above). Letting  $\lambda_{t+1} = \lambda_t$  and  $D_{t+1} = D_t, \forall t$ , we can identify three equations that characterize the steady-state conditions:

$$B'(W) + \frac{1}{\pi} \frac{\partial v}{\partial h} \frac{\partial g}{\partial W} = c, \quad (3.10a)$$

$$\left( s_1 s_2 + s_2 \frac{\partial g}{\partial D} - 1 \right) + \frac{\pi s_2}{\partial v / \partial h} \alpha = r, \text{ and} \quad (3.10b)$$

$$(1 - s_1 s_2) D = s_2 (g(D, W) - \pi h). \quad (3.10c)$$

Once parameters and functional forms have been determined, the three equations in (3.10) are used to solve for steady state levels of harvest, ponds and duck population in the base case. We then determine how the base case steady state results change as climate changes by exogenously decreasing  $W$  in equations (3.10) based on estimates from either equation (3.3) or (3.4), and future climate scenarios described in a later section.

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<sup>14</sup> The marginal cost of providing an additional pond need not be constant, but could be a function of the number of ponds, so that we would write  $c(W_t) = dC/dW_t$ .

<sup>15</sup> Notice also that functions  $v(\cdot)$  and  $g(\cdot)$  are taken to be non changing over time. Further, the last condition says that either it is optimal to drive the duck population to zero at some future time or the present shadow value of an additional duck is zero – a complementary slackness condition.

## Calibrating the Bioeconomic Model

The current bioeconomic model and subsequent calibration is very similar to that of van Kooten et al. (2011), presented in Chapter 2 above. The contribution of the current study is combining this model with a climate regression model to understand the impact of climate change on optimal wetlands retention. Therefore, the current section briefly outlines the calibration of this model, which is consistent with Chapter 2 above (van Kooten et al. 2011).

First, we adapt the valuation equation estimated by Brown and Hammack (H&B 1973) and adjust all values by the U.S. CPI. The resulting function is  $v(h) = 1.62 h^{0.409}$ , which is adjusted by weighting it by the number of hunters. The final valuation function used is  $v(h) = 114.58 h^{0.4}$ , with  $v(h)$  and  $h$  measured in millions.

Second, the values for the marginal cost and marginal benefit of wetlands that are used in this study are taken from the literature. The marginal benefit equals the social benefit of wetlands, and includes the non-use value as well as the value of ecological services such as carbon sequestration, filtering of water and flood control (Brander et al. 2006). Several studies estimate the marginal benefit of wetlands, and Woodward and Wui (2001) and Brander et al. (2006) used meta-regression analysis to estimate the ecosystem service values of wetlands. More relevant to the PPR study area, Belcher et al. (2001) estimated the benefits of wetlands retention in Saskatchewan. From this literature, we find that wetlands range in value between \$39.62 (based on Belcher et al.) and \$338 per hectare (based on Woodward and Wui), or \$11 and \$91 per pond. The lower value is from Belcher et al. (2001), which is used in this study as it is based on a similar region.

The cost of retaining wetlands is a net opportunity cost. It represents the loss of income from not having the land in its highest-valued alternative use, likely cropland. In addition to the opportunity cost, there is a one-time cost of restoring wetlands. Given that we are estimating the optimal value of wetlands, which may or may not be above historic levels (and may require retention and/or restoration), we must consider both costs. As indicated in Chapter 2 above, the sum of the annualized restoration cost and the opportunity costs is found to range broadly from \$20 to \$55 per pond. We conservatively assume a baseline cost of \$55.

Third, a logistic growth function of the following form is estimated for ducks:

$$g(D_t, W_t) = rD_t \left( 1 - \frac{D_t}{gW_t^b} \right) \quad (3.11)$$

where  $gW_t^b$  is the carrying capacity of the prairie pothole ecosystem. We have data on breeding ducks and immature offspring, and on wetlands (May pond counts), for the PPR (strata 26 through 40) over the period 1955 to 2007. We use the data to estimate equation (3.11) using non-linear least squares:

$$g(D_t, W_t) = 2.89D \left( 1 - \frac{D}{12.29W^{0.91}} \right), R^2 = 0.50, se = 7.79 \quad (3.12)$$

(8.73)    (4.20) (4.25)

The predicted change in wetlands under different climate scenarios works through the carrying capacity of the logistics function.

Finally, we employ Hammack and Brown's (1974) values for  $s_1$  and  $s_2$ : 0.95 and 0.80, respectively. Brown et al. (1976) assume 5% of duck kills are not reported, and we

use this factor to account for underreporting of bird kills by hunters. Loomis and White (1996) report non-use values for several endangered bird species, the smallest of which is \$8 per bird. Given the relative abundance of ducks, their value to viewers is likely to be much lower than \$8 each. We simply assume that the amenity value of a duck is \$1.

## **Results for Various Climate scenarios**

### *Climate change and the impact on wetlands*

We can estimate the effect of predicted climate change on wetlands using the results of regression equations (3.3) and (3.4). Our climate change scenarios are based on Larson (1995), Sorenson et al. (1998) and Johnson et al. (2005), who also examined wetlands.

The climate scenarios we consider are the following:

- (i) an increase in temperature of 3°C, no change in precipitation;
- (ii) no increase in temperature, a decrease in precipitation of 20%;
- (iii) an increase in temperature of 3°C, a decrease in precipitation of 20%; and
- (iv) an increase in temperature of 3°C, an increase in precipitation of 20%.

For specification (3.3), we first estimate the corresponding change in SPI due to changes in temperature and precipitation, and then the effect of SPI on wetlands using the coefficient on  $SPI_{t-1}$ . For specification (3.4), we estimate the effect of climate change on wetlands using the estimated coefficients on  $P_{t-1}$  (precipitation) and  $T_{t-1}$  (temperature), and then changing  $P$  and  $T$  by the amounts indicated. We solve the bioeconomic model for the base case (current) climate parameters and then solve it again for each of the above climate scenarios by changing the wetlands variable ( $W$ ) as indicated in Table 3.2.

In this way, we can determine the effect of climate change on optimal wetlands, ducks and harvests.

Projections of the impact on wetlands of the various climate scenarios described above are provided in Table 3.1. The results are similar for the two regression equations – one based on a drought index (equation 3.3) and the other on temperature and precipitation (equation 3.4). The magnitude of wetlands loss is similar, and the effect of temperature is larger than the effect of precipitation on wetlands in both models. This is consistent with previous studies (Sorenson et al. 1998; Larson 1995; Poiani and Johnson 1991). Note that the decrease in wetlands due to climate is larger across all scenarios using equation (3.4); in particular, increasing temperature by 3°C with no change in precipitation will decrease wetlands by around 20% based on equation (3.3) and by 27% based on equation (3.4). Further, increasing temperature by 3°C and increasing precipitation by 20% decreases wetlands by 7-10 percent, a small impact but similar to that found by Johnson et al. (2005). Increasing temperature by 3°C and decreasing precipitation by 20% will decrease wetlands by between 34 and 47 percent, which is similar to Larson's (1995) finding for comparable climate scenarios.

**Table 3.1 Effect of Alternative Climate Scenarios on Wetlands: Percent Decrease in Wetlands**

Regression Model	Scenarios			
	+3°C Temperature	-20% Precipitation	+3°C & -20% Precip	+3°C & +20% Precip
Equation (3.3)	20	13	34	7
Equation (3.4)	27	19	47	10

*Effect of climate change on optimal wetlands retention*

The base case, steady-state solutions are found by solving the system of equations (3.10) in the basic model. We use the functions and parameters presented in Table 3.2. In Table 3.3, we compare optimal values of ducks, ponds and harvests in the base model to historic values, and, finally, in Table 3.4 provide estimates of the optimal values under the various climate change scenarios described above.

The socially optimal values of wetlands, ducks and harvests are all higher than historic levels, as indicated in Table 3.3. This result is consistent with the findings of van Kooten et al. (2011) and Hammack and Brown (1974), and should not be surprising given that wetlands retention is based on private decisions that do not take into account externality effects. The effects on wetlands of climate change vary a great deal depending on the projected future climate scenario (Table 3.1). Declining wetlands can in turn have a severe impact on the optimal management strategies for wetlands and waterfowl, as is evident from the results in Table 3.4.

**Table 3.2: Model Functions and Parameters used in the Simulations**

Item	Base Case Parameter Values
Marginal hunter benefit function	$\partial v/\partial h = 46.8 h^{-0.6}$
Marginal product of wetlands in duck production	$\partial g/\partial W = 0.214D^2W^{-1.91}$
Marginal product of breeding ducks	$\partial g/\partial D = 2.89 - 0.470DW^{0.91}$
Intra-year duck survival rates	$s_1 = 0.95, s_2 = 0.80$
Marginal cost of protecting wetlands	$c = C'(W) = \$ 55$
Marginal amenity value of wetlands	$B'(W) = \$11$
Marginal non-hunting value of a duck	$\alpha = \$1$
Adjustment for underreporting of kills	$\pi = 1.35$

**Table 3.3 : Historic and Steady State Values of Ponds, Ducks and Harvests (millions)**

	Ponds ( $W$ )	Ducks ( $D$ )	Harvests ( $h$ )
Historic <sup>a</sup>	3.5	13.5	12.3
Base case <sup>b</sup>	4.1	20.3	19.6

<sup>a</sup> Source: Ponds and ducks are for Canada's prairie region and based on the average of 1955-2008 data from the U.S. Fish and Wildlife Service (<http://mbdcapps.fws.gov/>); harvest is the average of total 2007-2008 U.S. harvest

([www.fws.gov/migratorybirds/NewReportsPublications/HIP/hip.htm](http://www.fws.gov/migratorybirds/NewReportsPublications/HIP/hip.htm)).

<sup>b</sup> Based on bioeconomic model that takes into account amenity values of wetlands and ducks.

**Table 3.4: Steady State Values of Ponds, Ducks and Harvests (millions): Base Case and Climate Change Effects<sup>a</sup>**

Regression Model →	Base case	<i>Scenario i</i>		<i>Scenario ii</i>		<i>Scenario iii</i>		<i>Scenario iv</i>	
		(3.3)	(3.4)	(3.3)	(3.4)	(3.3)	(3.4)	(3.3)	(3.4)
Ponds ( $W$ )	4.1	3.4	3.2	3.7	3.5	3.0	2.6	3.9	3.8
Ducks ( $D$ )	20.3	13.8	11.8	15.9	14.1	9.9	6.85	17.9	16.9
Harvest ( $h$ )	19.6	13.4	11.5	15.4	13.7	9.7	6.75	17.3	16.4

<sup>a</sup> Scenarios refer to the ones described in section 5, while (3.3) and (3.4) refer to the predicted levels of wetlands resulting from those climate scenarios as derived from estimated regression equations (3.3) or (3.4).

In the first three scenarios in Table 3.4, there are significant decreases in the amounts of wetlands that society should optimally retain as a result of climate change. Over all scenarios, however, the change in wetlands ranges between a decrease of 5% and 38% from base case levels. In all situations, the proportional decline in ducks and harvests is significantly higher than the fall in wetlands; as we have fewer wetlands, the model predicts that the ratio of ducks and harvests to wetlands will decrease. These ratios are determined primarily by the use of the estimated logistics production (growth) function (3.12) – the relation of ducks and harvests to wetlands is not a linear one. Clearly, with substantially fewer wetlands, the landscape cannot support the large duck populations that it currently does because, with climate change, the socially optimal levels of ducks and harvests are much smaller. These results illustrate the potentially severe effects of climate change on wetlands and migratory waterfowl in North America's duck factory.

## **Discussion and Concluding Observations**

During the 21<sup>st</sup> century, climate change is expected to lead to drier conditions in the prairie pothole region of western Canada. This will decrease the region's wetlands area and impact its ability to support waterfowl. To provide some indication of the expected changes, we specified two multiple linear regression equations that use drought and temperature-precipitation data to determine how climate variables impact wetlands in the PPR taken as a whole. We then solved a bioeconomic model to obtain the optimal values of wetlands, ducks and harvests under current and projected future climate scenarios.

The effect of climate change on wetlands in this study is consistent with that found in the literature. Further, the two specifications of our regression equation for wetlands produced similar results, suggesting that our conclusions are quite robust. We found that climate change can decrease wetlands by as much as 47 percent. Using a bioeconomic model, we determined base-line (no climate change) estimates of the optimal numbers of wetlands and waterfowl to retain. From this, we conclude that optimal values should be higher than historically observed levels, which confirms the results of Brown and Hammack (1973) and van Kooten et al. (2011). However, the same bioeconomic model finds that the optimal retention of wetlands under a changed climate could be significantly lower. Drier conditions lead to socially optimal levels of wetlands that are as much as 38% below current levels. Further, optimal numbers of waterfowl and duck harvests fall at a much higher rate than wetlands, because drier conditions can lead to situations where duck populations are significantly decreased from current levels. It is worth noting that we only model the change in wetlands quantity in this study and not wetlands quality. Johnson et al. (2010) demonstrate that wetlands quality will also decrease in a changing climate. Therefore, the results of this study may be considered conservative.

The results of our research have important policy implications. First, while agriculture can provide environmental benefits (viz., nesting cover for waterfowl provided by winter wheat and grassland), soil erosion and loss of wetlands constitute major environmental problems associated with agricultural activities (Claassen et al. 2001). Indeed, wetlands have been drained for over a century and continue to be drained for agricultural development (Watmough and Schmoll 2007). This is due primarily to

market failure. Landowners receive none of the benefits of preserving wetlands, but incur the costs associated with foregone agricultural production, while hunters, many of whom are American, benefit from ducks produced in Canada. Our research incorporated the social benefits of wetlands and waterfowl, and showed that wetlands are and have historically been too few. Consequently, we argue that agricultural policy needs to consider the tradeoff between increased agricultural production and the loss of benefits from wetlands conversion. Greater emphasis needs to be placed on programs and policy that internalize the external benefits of wetlands by providing subsidies or tax credits that encourage private landowners to retain and/or restore wetlands. Some of the incentives should be paid for by American hunters, who benefit from the externality. Since duck hunters currently pay for wetlands retention in Canada through duck stamp programs, it is clear that other people in addition to duck hunters (i.e. tax payers) must also pay landowners in order to reach optimal wetlands levels. This is particularly true because all of society benefit from the many services that wetlands provide, such as carbon storage, prevention of soil erosion, and the provision of wildlife.

Second, our research has implications regarding adaptation to climate change. Policy options for reducing greenhouse gas emissions include, among others, increased renewable energy and biofuel production, energy conservation, and carbon sequestration in forests and wetlands. Our results show that climate change could significantly reduce wetlands, which adversely impacts the mitigation of greenhouse gases as wetlands are a carbon and methane sink (Brander et al. 2006). If climate change decreases wetlands, thereby triggering further release of CO<sub>2</sub> and CH<sub>4</sub> to the atmosphere, protection and restoration of wetlands is even more important.

Finally, this research has direct implications for hunting policies in and around the PPR. In particular, the length of the hunting season and the bag limit are important policy decisions. For example, Johnson et al. (1997) used a stochastic dynamic programming framework to address uncertainty related to random environmental and population variations and incomplete control over hunters' decisions. They find that, as wetlands in Canada's PPR increase, the optimal management strategy is to have a more liberal hunting regime (longer hunting seasons and higher bag limits). Although our bioeconomic model is deterministic, our results also indicate that, if wetlands increase (decrease), the optimal duck management policy is to encourage (discourage) hunting. That is, if the optimal numbers of ponds to preserve is higher than historical levels, optimal duck harvests should also be higher than historical levels.

Several elements are missing from the model, affording opportunities for potential extensions. As noted, uncertainty will have impact optimal decision making, especially when the uncertain nature of projected climate change for the study region is introduced. This uncertainty needs to be explicitly modeled (Johnson et al. 1997).

Bioeconomic models also need to consider spatial aspects that affect the selection of breeding sites by returning birds. Waterfowl do not disappear when wetlands are reduced and models must consider where birds may migrate. Johnson et al. (2005) estimate that suitable waterfowl habitat in the prairie pothole region will likely shift to the north and east due to climate change, while results from Wong et al. (2010) suggest that the availability of wetlands in northern parts of a flyway when southern wetlands are dry reduces the marginal values of wetlands. While we have shown that climate change can impact waterfowl habitat in the PPR, the next step is to determine whether waterfowl

populations can breed in more northerly climates and whether their productivity can be maintained. Whether waterfowl populations can be sustained elsewhere will impact how conservationists manage wetlands in the face of climate change.

Wetlands are also adversely impacted by policies that seek to mitigate climate change, particularly policies that subsidize production of corn, canola and other crops for biofuels, as their production increases the value of land in agriculture relative to wetlands. While this aspect of wetlands preservation and restoration was ignored in the current study, it must be taken into account along with the spatial and uncertainty aspects in future research. Both of these elements are considered in Chapters 4 and 5.

## **Chapter 4**

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

### **Introduction**

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

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

Given that, in the PPR, significant use and non-use benefits derive from wetlands and waterfowl (van Kooten et al. 2011), it is important that these benefits be considered

in any analysis regarding the retention of wetlands. It is also important to understand how climate change might impact wetlands, and how decisions to manage wetlands are affected by climate change and mitigation policies. Specifically, it is important to determine how policies that affect land management decisions, such as policies that affect demand for biofuels, will impact wetland values. Given uncertainty about future precipitation in the region, it is important to consider the effects of both a drier and wetter climate on wetlands and waterfowl management decisions. The objectives of the current research are therefore as follows:

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

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

estimate the impact on these variables of climate change and policies to mitigate it (in our case, incentives to increase biofuel production).

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

When calibrated to solve for historic values of wetlands, the model predicts that the shadow value of wetlands is much higher than the returns to cropping, because wetlands provide ecosystem benefits and produce waterfowl for viewing and hunting. The high shadow value indicates that too few wetlands have historically been retained in the PPR. Further, the effect of climate change is that the optimal level of wetlands to retain falls by as much as 37 to 56 percent from baseline values, depending upon the climate scenario. At the sub-region level, the effect of climate change on wetlands management is most pronounced in the province of Saskatchewan.

## **Background Literature**

Mathematical bioeconomic models are used to efficiently allocate renewable natural resources subject to ecological constraints. Many studies have looked at the optimal management of wildlife in a variety of settings, with models ranging from the analytic to numeric, from deterministic to stochastic, and from static to dynamic. In this

section, however, we provide a brief review only of studies of direct relevance to migratory waterfowl and the study region.

Gardner Brown and his colleagues (Brown and Hammack 1973; Hammack and Brown 1974; Brown et al. 1976) were the first to use mathematical bioeconomic models to address wetlands conservation in the context of migratory waterfowl in North America, most particularly ducks. They specified a discrete bioeconomic optimal control model of duck hunting that maximizes benefits to hunters minus the costs of providing wetlands. The objective function is constrained by population growth. The authors solved for the optimal values of wetlands, ducks and harvest. Their focus was solely on duck hunting values, ignoring other waterfowl values and wetland benefits.

Van Kooten et al. (2011) updated and re-parameterized the foregoing model, extending it to include the amenity values of both ducks and wetlands. Upon solving for the optimal levels of ducks, harvests and wetlands, these authors confirmed the original results of Brown and his colleagues. Withey and van Kooten (2011) then extended the van Kooten et al. (2011) model to consider the impact of climate change on wetlands management. Because wetlands in any given period were a linear function only of temperature and precipitation in the preceding period (i.e., a function of drought) and were not dependent on previous wetlands area, the decision to protect wetlands depended only on the wetlands area made available by the prevailing climate conditions and the impact that conservation of wetlands had on future duck viewing and hunting. Further, the impact of climate mitigation policies on cropping decisions and conversion of wetlands to cropland was ignored.

In this paper, we extend the above models to include cropping decisions in the objective function and wetlands as a separate state variable. We specify a separate dynamic, nonlinear wetlands state equation that relates direct climate impacts on wetlands in one year to wetlands availability in the next. Cropping decisions that affect wetlands retention across years are incorporated directly into the model as opposed to operating through the waterfowl dynamics. Thus, we can explicitly estimate the combined effect of climate change and climate-change related land-use policies on wetlands retention. Further, by including land use in the model, we are able to estimate the impact of a change in the demand for feedstock for biofuel production on land use and wetlands, which has not been done previously. Finally, we provide results on a provincial and sub-regional level in addition to results for the entire Canadian pothole region, which is useful for policy purposes.

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

Other studies have estimated the impact of climate change on wetlands, with several having used a multiple regression approach to estimate the impact of climate measures on wetlands in parts of the PPR (Larson 1995; Sorenson et al 1998). A detailed

review of this literature can be found in Withey and van Kooten (2011). As noted above, the current research goes beyond these studies because we estimate the optimal management of wetlands and waterfowl in the face of climate change, examining both direct climate effects as well as effects related to increased biofuel production.

### **Analytic Model**

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

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

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

$$\sum_{t=0}^{\infty} [v(h_t) + \alpha D_t + B(W_t) - C(W_t) + N(a_t)] \rho^t, \quad (4.1)$$

where  $v(h_t)$  is a function describing the benefits derived from harvesting  $h_t$  ducks at time  $t$ ;  $D_t$  refers to the population of ducks at  $t$ ; and  $B(W_t)$  and  $C(W_t)$  are the respective annual

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

Equation (4.1) is maximized subject to a bioeconomic constraint describing the duck population dynamics and another describing the change in wetlands. Ducks breed in the PPR in May and begin the fall flight south in September, which is also the start of hunting season. The fall flight consists of the fraction  $s_1$  of May breeding ducks  $D_t$  that survive to September, plus offspring that survive to September. The latter is given by the recruitment function  $g(D_t, W_t)$ . In the fall,  $h_t$  ducks are harvested, and the remaining ducks represent the winter population. Of this,  $s_2$  ducks will survive and return in the spring to breed. The population dynamics for ducks are represented by the following equation:

$$D_{t+1} = s_2 [s_1 D_t + g(D_t, W_t) - \pi h_t]; \quad (4.2)$$

$$D_t, h_t, W_t \geq 0; \text{ and } D_0 > 0, W_0 > 0 \text{ given}; \quad (4.3)$$

where  $D_{t+1}$  is the number of mature ducks returning to the prairie pothole breeding grounds in year  $t+1$ ,  $s_1$  is defined above,  $s_2$  is the fraction of mature ducks that are not killed by hunters and survive to return to the breeding grounds in year  $t+1$ , and  $\pi > 1$  accounts for the loss of ducks that are killed or maimed by hunters but not collected or reported. Conditions (4.3) are non-negativity constraints and initial conditions.

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

$$W_{t+1} = \beta_0 + \beta_1 W_t e^{SPI_t}, \quad (4.4)$$

$$\bar{A} = W_t + a_t, \quad (4.5)$$

$$W_t, a_t \geq 0; a_0, W_0, SPI_0 \text{ given}; \quad (4.6)$$

where  $a_t$  refers to the cultivated area in period  $t$ . Wetlands in a given period are a function of wetlands in the preceding period and climate. As a measure of climate and climate change, we use the standardized precipitation index (*SPI*), which is in fact a drought index. This index ranges from -4 to 4, where relatively wet seasons are greater than zero and relatively dry seasons are less than zero. The total land area available at any given time is denoted  $\bar{A}$ , and this land can be in wetlands (including undeveloped uplands habitat) or cropland (including pasture and summer fallow). We ignore factors that might result in the conversion of unimproved forest and range land into agriculture, as this occurs at the extensive margin; our interest here is the intensive margin, where wetlands in the agricultural zone are being converted to cropland (see van Kooten and Bulte 2000,

pp.59-73). We hypothesize that changes in wetland area are impacted by climate and the conversion of land to cropland. Finally, the  $\beta_i$ s are parameters to be estimated.

The Lagrangian associated with the above bioeconomic problem is:

$$L = \sum_{t=1}^{\infty} \left\{ \rho^t \left[ (v(h_t) + \alpha D_t + B(W_t) - C(W_t) + N(a_t)) + \theta_t (\bar{A} - W_t - a_t) \right] + \rho^{t+1} \left[ \lambda_{t+1}^D [(s_1 s_2 - 1) D_t + s_2 g(D_t, W_t) - s_2 \pi h_t + D_t - D_{t+1}] + \lambda_{t+1}^W [\beta_0 + W_t (\beta_1 e^{SPI_t} - 1) + W_t - W_{t+1}] \right] \right\} \quad (4.7)$$

where  $L$  is the Lagrange function, and  $\lambda_{t+1}^D$  and  $\lambda_{t+1}^W$  are the shadow prices of an additional duck and wetland acre, respectively. Equation (4.7) can be solved by finding the first-order conditions for each control and state variable in each period, that is by setting  $\partial L / \partial h_t = 0$ ,  $\partial L / \partial a_t = 0$ ,  $\partial L / \partial D_t = 0$  and  $\partial L / \partial W_t = 0$ . One also needs to take into account the constraint equations, which can be recovered from (4.7) through

differentiation as follows:  $\frac{\partial L}{\partial \lambda_{t+1}^D} = 0$  and  $\frac{\partial L}{\partial \theta_t} = 0$ .

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

$$\frac{\partial L}{\partial h_t} = v'(h_t) - \rho \lambda_{t+1}^D \pi s_2 = 0 \quad (4.8)$$

$$\frac{\partial L}{\partial a_t} = N'(a_t) - \theta_t = 0 \quad (4.9)$$

$$\frac{\partial L}{\partial D_t} = \alpha + \rho \lambda_{t+1}^D \left( s_1 s_2 - 1 + s_2 \frac{\partial g}{\partial D_t} \right) + \rho \lambda_{t+1}^D - \lambda_t^D = 0 \quad (4.10)$$

$$\frac{\partial L}{\partial W_t} = B'(W_t) - c - \theta_t + s_2 \rho \lambda_{t+1}^D \frac{\partial g}{\partial W_t} + \rho \lambda_{t+1}^W (\beta_1 e^{SPI_t} - 1) + \rho \lambda_{t+1}^W - \lambda_t^W = 0 \quad (4.11)$$

Differentiating with respect to the Lagrange multipliers yields conditions (4.2), (4.4) and (4.5). For convenience, we have assumed  $C'(W_t) = c$ , a constant, which is the annual cost of providing an additional pond; and  $dN/da_t = N'(a_t)$  is the marginal net revenue from cropping the next acre taken out of wetlands.

Maximum principle (4.8),  $(1/\pi) \partial v / \partial h_t = \rho \lambda_{t+1}^D s_2$ , says that hunting should continue until the value of the marginal duck that is harvested (adjusted for the fact that not all birds killed are recovered) equals the user cost of taking that bird. The user cost equals the discounted shadow value of leaving the duck in situ adjusted for the fact that not all unharvested ducks survive to breed the following spring.

Maximum principle (4.9),  $N'(a_t) = \theta_t$ , says that farmers should continue to crop to the point where the marginal revenue of the last acre equals the shadow value of adding another acre to the total land base (i.e., at the extensive margin). In the current model, this value is equal to the value of land that is not currently cropped, but which will be put into crop production should crop prices rise ever so slightly.

Equations (4.10) and (4.11) are dynamic arbitrage conditions. Condition (4.10),

$$\rho \lambda_{t+1}^D (s_1 s_2 + s_2 \frac{\partial g}{\partial D_t}) = \lambda_t^D - \alpha,$$

requires hunters to take into account the value of allowing some ducks to escape so they can breed and produce more birds that are then available to future hunters and viewers. The discounted future (shadow) value of allowing a duck to escape (adjusted for mortality and the marginal growth in duck population) must equal the current (shadow) value of harvesting that duck less the amenity value of the duck.

$$\text{Similarly, condition (4.11), } \rho \left[ s_2 \lambda_{t+1}^D \frac{\partial g}{\partial W_t} + \lambda_{t+1}^W \beta_1 e^{SPt} \right] = \lambda_t^W + [c - B'(W_t) + \theta_t],$$

requires that consideration be given to the future value of wetland retention when deciding on whether to drain an additional wetland for agricultural use. That is, decision makers must retain (or drain) wetlands so that the current value of a wetland, as given by the shadow value of the wetland less the (opportunity) cost of retaining it, is equal to the future discounted value of the marginal wetland. The latter is determined by the future value of wetlands in the production of ducks plus the actual future shadow value of the wetland in providing amenities to society.

A steady-state solution is found by letting  $\lambda_{t+1}^W = \lambda_t^W$ ,  $W_{t+1} = W_t$ ,  $\lambda_{t+1}^D = \lambda_t^D$  and  $D_{t+1} = D_t$ ,  $\forall t$ . Letting a superscript \* denote the optimal steady-state value of a variable, we obtain from state equations (4.4), (4.5) and (4.2), respective results (4.12), (4.13) and (4.14).

$$W^* = \beta_0 / (1 - \beta_1 e^{SPt}) \quad (4.12)$$

$$a^* = \bar{A} - W^* \quad (4.13)$$

$$D^* = s_2 [s_1 D^* + g(D^*, W^*) - \pi h^*] \quad (4.14)$$

We can derive the shadow price of land from the maximum principle (4.9) as:

$$\theta^* = N'(a^*) \quad (4.15)$$

Recalling that  $\rho = 1/(1+r)$ , we obtain the shadow value of ducks from (4.8) as:

$$\lambda^{D^*} = \frac{(1+r)v'(h^*)}{\pi s_2} \quad (4.16)$$

However, we can also find an expression for the shadow value of ducks from (4.10) as:

$$\lambda^{D^*} = \frac{(1+r)\alpha}{(1+r) - s_1s_2 - s_2 \frac{\partial g(D^*, W^*)}{\partial D^*}} \quad (4.17)$$

Upon equating (4.16) and (4.17), we find

$$v'(h^*) = \frac{\pi\alpha s_2}{(1+r) - s_1s_2 - s_2 \frac{\partial g(D^*, W^*)}{\partial D^*}}, \quad (4.18)$$

which can be used to find an optimal value for  $h^*$ . Finally, upon solving equation (4.11)

and substituting for the steady-state value of  $\lambda^{D^*}$  from (4.16), we obtain the following expression for the steady-state shadow value of wetlands:

$$\lambda^{W^*} = \frac{\pi[B'(W^*) - c - N'(a^*)] + v'(h^*) \frac{\partial g(D^*, W^*)}{\partial W^*}}{\pi(1 - \rho\beta_1 e^{SPI})} \quad (4.19)$$

Once functional forms for  $N(\cdot)$ ,  $v(\cdot)$ ,  $g(\cdot)$  and  $B(\cdot)$  are specified, and the parameters  $s_1$ ,  $s_2$ ,  $\rho$  (or discount rate  $r$ ),  $\alpha$ ,  $c$ ,  $\beta_1$  and  $\pi$  are determined, we can find the duck population ( $D^*$ ), harvests ( $h^*$ ), cropland area ( $a^*$ ) and wetlands area ( $W^*$ ) that maximize the planner's well being in the long run. These are found by simultaneously solving equations (4.12), (4.13), (4.14) and (4.18). Further, once the optimal values of the control and state variables are known, we can find the shadow prices of land ( $\theta^*$ ), ducks ( $\lambda^{D^*}$ ) and wetlands ( $\lambda^{W^*}$ ) by solving (4.15), (4.16) and (4.19), respectively.

The two drivers in the model are changes in the drought measure, SPI, which enters through equations (4.12) and (4.19), and changes in net returns to cropping, which

only impact the shadow prices of land and wetlands through equations (4.15) and (4.19), respectively. Clearly, drought will affect the optimal allocation of land between agriculture (cropland) and wetlands, but changes in net returns to cropping activity have no direct impact. The reason is that, as long as the marginal net return to cropping  $N'(a) > 0$  is not upward sloping in the neighborhood of the intensive margin (i.e., as long as  $N''(a) \leq 0$ ), result (4.13) implies that  $W^*$  and  $a^*$  do not depend on the functional form of  $N(a)$ . The problem is that, while we desire to separate land uses for food crops, energy crops and wetlands, the model is too nonlinear and has too many state plus control variables to be analytically tractable. This is discussed further in the results section and in the conclusions where we point out that a numerical mathematical programming model is required to address multiple land uses in this context.

The model determines the optimal levels of cropland, wetlands, ducks and duck harvests. Since wetlands have a higher social than private value, the authority must provide incentives to landowners if the desired outcome is to be achieved. Since the incentives needed are a function of the shadow prices  $\theta^*$  and  $\lambda^{W^*}$  for cropland and wetlands, such values are important for policy purposes, and they depend crucially on  $N'(a^*)$ .

## **Parameterization and Results**

We parameterize and solve the preceding analytical model for Canada's entire PPR, as well as for disaggregated regions of the PPR. This creates a bit of a dilemma, however, because optimal duck harvests are determined at the supra-regional level and not the sub-region or provincial level. The problem cannot be addressed simply by

imposing the supra-regional optimal harvests on the regions because there is no straightforward way to allocate the entire harvest to a sub-region. Our approach, therefore, is to examine the allocation *ex post*. If the sum of the (optimal) sub-region level harvests are ‘close’ to optimal overall harvest, we can be confident of the general robustness of our model.

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

#### *Entire region results*

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

Estimates of the annual marginal environmental service and other amenity benefits of wetlands are based on meta-regression analyses by Woodward and Wui (2001), Brander et al. (2006), and Cortus et al. (2011). Data from the latter study are particularly important for our purposes because they adapt estimates from Belcher et al. (2001) of the social benefit of wetlands for a region in Saskatchewan. Estimates from

Cortus et al. (2011) range between \$16 and \$51 per acre, compared with mean wetland values of \$60/ac for North America reported by Brander et al. (2006). For simplicity, we assume a constant marginal benefit of \$45 per acre, which includes the benefits of wetlands in mitigating climate change (Cortus et al. 2011). The annualized restoration cost plus opportunity cost of retaining the marginal wetland is determined using data from Cortus et al. (2011) and Hansen (2009), and ranges between \$20 and \$55 per pond, or \$17 and \$46 per acre (see van Kooten et al. 2011). These values include the opportunity cost of retaining wetlands, which would be the equivalent of the net return to cropping as used in this model. Thus, for our base case scenario, we assume a lower level of \$10/ac for the annual marginal (restoration) cost of retaining wetlands.

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

$$g(D_t, W_t) = \eta D_t \left( 1 - \frac{D_t}{\gamma W_t^b} \right), \quad (4.20)$$

where  $\gamma W_t^b$  is the carrying capacity of the prairie pothole ecosystem and  $\eta$  is the intrinsic growth rate. We use data on breeding ducks and immature offspring, and on wetland habitat (May ponds converted to acres based on average pond counts of 0.85 acres (Hammack and Brown 1974)), for Alberta, Saskatchewan and Manitoba, encompassing strata 26 through 40 (Figure 4.1), for the period 1955 to 2008 (U.S. Fish and Wildlife Service 2010). Using nonlinear least squares regression, we estimate the following:

$$g(D_t, W_t) = 2.85 D \left( 1 - \frac{D}{14.25 W^{0.91}} \right), \quad R^2 = 0.56, \quad (4.21)$$

(10.08)                      (4.76) (4.61)

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

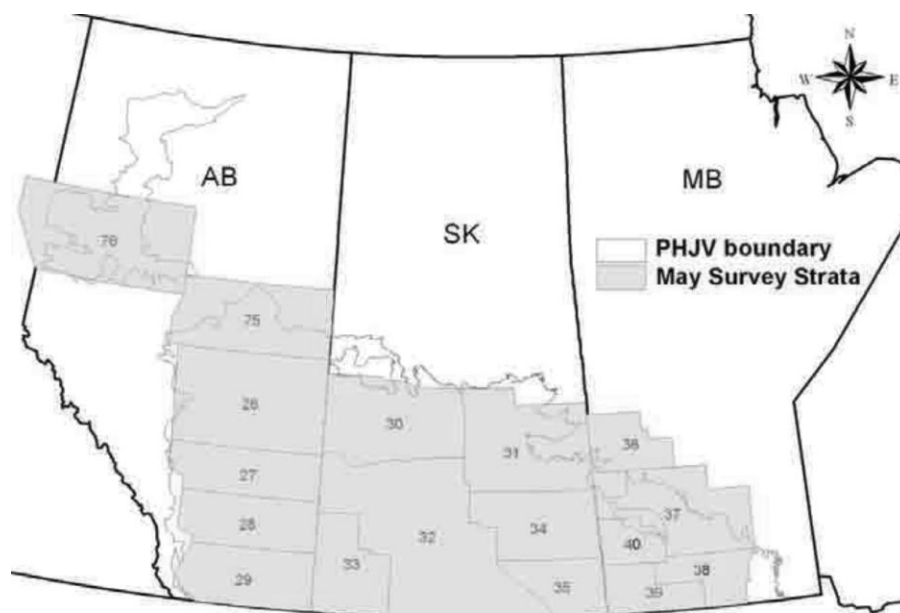


Figure 4.1: US Fish and Wildlife Service May Survey Strata (PHJV, 2009)

The wetlands state equation (4.4) is also parameterized using nonlinear least squares regression. As noted, wetlands data are available from the U.S. Fish and Wildlife Service (2010). SPI data are from the North American Drought Monitor;<sup>16</sup> the SPI variable was constructed using averages from several weather stations in the study region. The SPI ranges from  $-4$  to  $+4$ , with negative values indicating dry conditions and positive values wet ones. A value of  $-1$  or less is an indicator of drought, with drought severity increasing as the SPI value falls. The estimated wetlands equation is as follows:

$$W_{t+1} = 1.91 + 0.32W_t e^{SPI_t}, R^2 = 0.24, \quad (4.21)$$

(6.92) (3.99)

where t-statistics are again provided in parentheses. All estimated coefficients have the expected sign and are statistically significant at the 1% level.

<sup>16</sup> Retrieved online at <http://www.ncdc.noaa.gov/temp-and-precip/drought/nadm/>

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

A summary of the base-case functional forms and parameter values is provided in Table 4.1. Using these and solving equations (4.12) through (4.18), we find the base scenario, steady-state values of the variables  $W^*$ ,  $D^*$ ,  $h^*$ ,  $a^*$ ,  $\lambda^{D^*}$ ,  $\lambda^{W^*}$  and  $\theta^*$  (Table 4.2).

**Table 4.1: Model Functions and Parameters used in Simulations**

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

**Table 4.2: Historic and Steady State Values of Wetlands (W) , Duck Population (D), Duck Harvest (h) and Cropped Area (a)**

	Wetlands ( $\times 10^6$ acres)	Ducks ( $\times 10^6$ )	Duck harvests ( $\times 10^6$ )	Cropped area ( $\times 10^6$ acres)	Shadow value of ducks (\$/duck)	Shadow value of wetlands (\$/ac)
Historic <sup>a</sup>	2.95	13.10	12.30	80.60	–	–
Base case <sup>b</sup>	2.80	16.82	15.35	80.77	8.84	59.66

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

<sup>b</sup> Based on bioeconomic model that takes into account amenity values of wetlands and ducks.

The base-case model outcome leads to the retention of 2.8 million acres of wetlands, which is lower than historic levels. In theory, the model should solve for the historic value of wetlands, but the value is slightly different due to white noise in estimating regression equation (4.4). Notice that, when the model (approximately) calibrates to historic values of wetlands, the shadow value of wetlands is \$59 per acre, which is higher than the return to cropping. This suggests that it is socially beneficial to have more lands in wetlands, indicating that the historic area in wetlands is lower than socially desirable as decisions to conserve wetlands are based almost solely on private values. This result is similar to that of the earliest bioeconomic studies (Brown and Hammack 1973). We employ 2.8 million acres as our base case, and estimate the effect of climate change relative to this level.

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

more ducks should be permitted to return to the breeding grounds than is currently the case.

#### *Results by province and stratum*

By solving the model for each sub-region, we can provide policymakers with more information that might enable them to better focus wetlands conservation efforts. We can also get an idea of where climate change effects on wetlands will be the most pronounced. To solve the regional models, however, it is necessary to make changes to the values in Table 4.1; it is necessary to re-parameterize equations (4.12) through (4.19) for each province and stratum separately, and then solve the model for each sub-region.

First, consider the logistic growth function and wetland state equations for each province and stratum. Data are available on wetlands and waterfowl for each stratum from the U.S. Fish and Wildlife Service's (2010) Annual May Waterfowl Survey, while climate data are from weather stations in each of the 15 strata. The parameter values from estimated logistic equation and wetlands state equation are provided in Table 4.3.

Waterfowl population data at the disaggregated (strata) level are much more varied than aggregate data, which produced unrealistic parameter estimates for the logistic equation (4.19) in several strata. Upon excluding outliers for wetlands and ducks in some strata, we obtained a better statistical fit; in Table 4.3, therefore, we include the number of observations used to estimate the logistic function, with 54 observations (1955-2008) available. For some strata with very volatile data (strata 29, 30 and 36), a significant number of observations were eliminated. The wetland state equation (4.4), on the other hand, was estimated using all available observations for 1955-2008.

**Table 4.3: Sub-Region Parameter Estimates for the Logistic and Wetland State Equations by Strata and Province**

<i>Strata</i>	<i>Obs.</i>	Logistic function			Wetlands State	
		$\eta$	$\gamma$	$b$	$\beta_0$	$\beta_1$
26	47	3.08*	11.58*	0.61*	0.26*	0.27*
27	46	2.64*	11.30*	0.74*	0.08*	0.20*
28	48	2.65*	8.70	0.42	0.07*	0.14
29	39	2.64*	4.75**	0.50**	0.07*	0.16*
30	24	3.13*	21.90*	1.14*	0.17*	0.25*
31	43	2.18*	38.80*	1.48**	0.27*	0.25*
32	44	2.80*	23.90*	0.94*	0.31*	0.24*
33	54	2.85*	15.50*	0.86*	0.08*	0.11
34	54	3.04*	8.42*	0.71*	0.25*	0.29*
35	54	2.30*	29.60	0.70	0.14*	0.31*
36	35	2.25*	8.87	0.98	0.04*	0.19*
37	54	2.48*	16.50	0.94	0.19*	0.14**
38	47	2.45*	1.78	0.63*	0.03*	0.20**
39	44	2.51*	17.71	1.05*	0.08*	0.32*
40	54	2.87*	3.97*	0.41	0.10*	0.16**
<i>Province</i>						
Manitoba	51	3.02*	7.19*	0.64*	0.43*	0.24*
Saskatchewan	47	2.80*	14.90*	1.11*	1.17*	0.28*
Alberta	46	3.12*	13.28*	0.67*	0.46*	0.27*

<sup>a</sup>  $\eta$ ,  $\gamma$  and  $b$  are the parameters in the logistic equation (20);  $\beta_0$  and  $\beta_1$  refer, respectively, to the intercept and slope parameters in equation (4.4); \* (\*\*) indicates statistical significance at the 5% (10%) level.

Second, the hunter valuation function in Table 4.1 is calibrated on the basis of PPR-wide harvest levels. Following the approach employed by van Kooten et al. (2011), we re-specify the valuation function as  $v(h) = 61h^{0.409}$  for provincial analysis and  $v(h) = 27h^{0.409}$  for each stratum. However, this assumes that hunters value ducks the same regardless of where they breed. To the extent that ducks are hunted only by Americans, this is likely true; but if the valuation function includes local residents this might not be the case. Nonetheless, this assumption is necessitated by the lack of valuation information.

Finally, we adjust the net revenue from cropping by province and stratum. While information is available from Statistics Canada to facilitate this for provinces, we lack stratum-level data on revenue. As a result, we adjust the net revenue in Table 4.1 using crop yields for wheat, barley and oats. These are the most prominent crops for which data are available for all sub-regions. We multiply the net revenue by the crop yield averaged over these crops in a given stratum and divide by the average yield for the entire PPR.

The steady-state values for wetlands area, duck population, duck harvests and cropland by province and strata are provided in Tables 4.4 and 4.5, respectively. Historic data on duck harvests are not available at the sub-region (province or stratum) level, so only the aggregate levels for the PPR from Table 4.2 are reported.

**Table 4.4: Historic and Base Case Steady State Values of Wetlands Area (W), Duck Population (D), Duck Harvests (h) and Cropped Area (a), by Province (millions)**

Item	Province			TOTAL
	Alberta	Saskatchewan	Manitoba	
<i>Historic Values</i>				
Duck populations ( $\times 10^6$ )	4.30	7.50	1.30	13.10
Duck harvests ( $\times 10^6$ )	—	—	—	12.30
Wetlands ( $10^6$ acres)	0.64	1.72	0.59	2.95
Cropped area ( $10^6$ acres)	21.43	48.06	11.13	80.62
<i>Base Case Optimal Values</i>				
Duck populations ( $\times 10^6$ )	4.49	12.13	2.26	18.88
Duck harvests ( $\times 10^6$ )	4.49	10.51	2.26	17.34
Shadow value of a duck (\$)	9.73	5.9	14.84	10.15
Wetlands ( $10^6$ acres)	0.62	1.62	0.56	2.81
Cropped area ( $10^6$ acres)	21.45	48.16	11.15	80.76
Wetland shadow value (\$/ac)	60.63	68.02	30.71	53.12

**Table 4.5: Historic (H) and Optimal Steady-State (SS) Values of Wetlands (acres), Duck Population, Duck Harvests and Cropped Area (acres) by Stratum and Total (millions)**

Stratum	26		27		28		29	
	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>
Wetland	0.37	0.36	0.11	0.1	0.08	0.08	0.08	0.08
Ducks	2.45	2.8	0.71	0.96	0.63	1.36	0.5	0.59
Harvest		1.73		0.81		1.15		0.51
Crops	9.47	9.49	5.1	5.11	2.12	2.12	4.73	4.73
Stratum	30		31		32		33	
	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>
Wetland	0.24	0.22	0.38	0.36	0.42	0.4	0.09	0.08
Ducks	1.34	1.84	1.42	1.42	2.57	2.57	0.43	0.84
Harvest		1.84		1.42		1.64		0.78
Crops	8.45	8.47	7.86	7.88	18.22	18.24	3.41	3.42
Stratum	34		35		36		37	
	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>
Wetland	0.37	0.35	0.22	0.2	0.06	0.05	0.24	0.23
Ducks	1.04	1.86	0.69	0.69	0.06	0.22	0.55	1.87
Harvest		1.81		0.47		0.16		1.44
Crops	6.58	6.61	3.53	3.56	0.58	0.58	3.1	3.12
Stratum	38		39		40		<b>Total Region</b>	
	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>	<i>H</i>	<i>SS</i>
Wetland	0.04	0.04	0.13	0.11	0.13	0.12	2.95	2.78
Ducks	0.07	0.1	0.2	0.82	0.44	0.77	13.1	18.71
Harvest		0.08		0.66		0.72	12.3	15.25
Crops	3.02	3.02	2.93	2.94	1.49	1.5	80.62	80.79

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

Results from Tables 4.4 and 4.5 confirm the overall conclusion from Table 4.2. Wetlands retention is lower than historic averages, due to estimation of the wetlands state equation. However, the average shadow value of wetlands is higher than the return to cropping. Thus, it is socially optimal to increase wetlands above historic levels in the

steady state. Further, steady state levels of ducks and harvests are found to be higher than historic values, due to the value of ducks and harvests. The results of Tables 4.4 and 4.5 provide a base case from which to estimate climate change effects, which may be very different by sub-region.

Clearly, there are differences in results as one changes the level of aggregation. In particular, the socially optimal duck populations and duck harvests are higher in the disaggregated analysis, but this might be due to the particularly large estimated parameters on the carrying capacity for strata 31-37 (see Table 4.3). Nonetheless, the major results remain consistent across the three levels of analysis and the model provides a base case from which climate change effects can be estimated.

### **Effect of Climate Change on Wetlands Retention**

To estimate the impact of climate on the baseline values given in Tables 4.2, 4.4 and 4.5, we specify several climate change scenarios. We first present climate change scenarios that pertain to the entire PPR, and then discuss necessary adjustments to the scenarios for regional analysis, followed by our estimates of the effects of these policies.

#### *Policy scenarios*

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

- 1) an increase in temperature of 3°C, no change in precipitation;
- 2) an increase in temperature of 3°C, a decrease in precipitation of 20%; and
- 3) an increase in temperature of 3°C, an increase in precipitation of 20%.

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

$$SPI = -0.03 + 0.0018 \times Precipitation - 0.0695 \times Temperature, R^2 = 0.60 \quad (4.23)$$

(-0.14)    (5.68)
(-4.63)

SPI is the standardized precipitation index, precipitation is annual and temperature is the mean annual maximum temperature. Temperature and precipitation data are available from Environment Canada's Historical Weather and Climate Data.<sup>17</sup> At mean values of precipitation and temperature, the model predicts  $SPI = -0.02$ , which is the actual mean value for the PPR. For climate scenarios 1, 2 and 3, the corresponding SPI values predicted by the regression equation are  $-0.22$ ,  $-0.36$  and  $-0.08$ .

Climate change will also indirectly impact wetlands as a result of mitigation policies, particularly those that subsidize production of biofuel crops. In 2008, the Government of Canada introduced a Renewable Fuel Standard (RFS) that requires 5% renewable content in gasoline by 2010 and 2% renewable content in diesel and home

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<sup>17</sup> Retrieved online at [http://www.climate.weatheroffice.gc.ca/Welcome\\_e.html](http://www.climate.weatheroffice.gc.ca/Welcome_e.html)

heating oil by 2012.<sup>18</sup> This standard will increase demand for grains that are used to make biodiesel, and will increase production of canola in the prairie pothole region.

Mussell (2010) estimates that this policy will increase the price of canola by \$19 per tonne for the 2-percent blend, and \$200 for the 5-percent blend. Given current prices, the increase due to the RFS policy represents a 7.5% increase in the price of canola for the 2-percent blend and 79% increase for the 5-percent blend. Since the latter result seems quite high, we consider the impact of increasing the price of canola by 15%.

As discussed in the analytic model above, we are limited to two land uses. Therefore, we estimate the impact of the increase in canola price on land use (wetlands) in two ways. This is seen by solving (4.16) for  $v'(h^*)$  and then substituting this result, along with (4.12) and (4.15), into (4.19):

$$\lambda^{W^*} = \frac{\left[ (1+r)(B'(W^*) - c - \theta^*) + s_2 \rho \frac{\partial g(D^*, W^*)}{\partial W^*} \lambda^{D^*} \right] W^*}{rW^* + \beta_0} \quad (4.24)$$

Shadow prices  $\theta^*$  and  $\lambda^{W^*}$  refer to the extensive and intensive margins, respectively;  $\theta^*$  is the value of increasing the fixed land base ( $\bar{A}$ ), while  $\lambda^{W^*}$  is the marginal value of converting wetland to cropland. One way of dealing with the problem within the context of our model is as follows: Given  $\bar{A}$  in equation (4.13), it is necessary to determine the impact of an increase in the price of canola on land use in an exogenous fashion – any increase in canola acreage must come at the expense of wetlands, cultivated acreage currently producing food crops or in summer fallow, or some combination of these.

<sup>18</sup> Information from: [www.topcropmanager.com/content/view/4348/38/](http://www.topcropmanager.com/content/view/4348/38/) (accessed December 22, 2010).

The increase in area planted to canola as a result of the biofuel policy is dictated primarily by the increased price of canola. We estimate the impact of canola price on total cropland using the following estimated OLS regression based on 1985-2010 data:

$$a = 63.3 + 0.025 \times P_c, R^2 = 0.57, \quad (4.25)$$

(26.04)    (3.38)

where  $a$  is the total area of cultivated land planted to crops (million ac),  $P_c$  is the price of canola (\$/tonne) obtained from Statistics Canada, and  $t$ -values are provided in parentheses. Based on result (4.25), a 15% increase in the price of canola will increase cropped area by 1.25 million acres. Because it incorporates all cropped land plus summer fallow, we assume that the increase in canola acreage will increase total land in crops ( $a$ ) rather than replacing land in other crops or summer fallow. Therefore, the increase in canola comes solely at the expense of wetlands. As discussed below, the estimates provided here under the biofuel policy scenarios should be considered an upper bound of the climate effects on wetlands retention, since all increases in canola may not come at the expense of wetlands.

In addition to the historic levels of wetlands, ducks, harvests and cropped acres, the model solves a baseline scenario that provides optimal values for these variables (Tables 4.2, 4.4 and 4.5). Then we consider the climate scenarios discussed above and, for each, consider a further impact from diverting 1.25 million acres of wetlands to the production of canola for biodiesel. We refer to these scenarios as 1F, 2F and 3F, and they represent the total (temperature and precipitation change plus biofuel policy) impact of climate change on optimal wetlands retention and waterfowl population. The same scenarios are investigated separately for each sub-region, whether provinces or strata. To

allocate the extra 1.25 million of cropped land among the provinces or strata, we simply increase cropped area in each sub region by the weight of historically cropped land in the stratum or province to total cropped land in the PPR.

As an alternative to the above approach, we can examine the problem from the perspective of a social planner who looks only at shadow prices. Clearly, the biofuel policy increases the marginal return to cultivated land  $N'(a)$ , which, as indicated in (4.19), will reduce the shadow value of wetlands and thereby the optimal area to retain as wetlands. In the steady state, a social planner will allocate land to crops and wetlands so that the social shadow value of wetlands equals the net marginal return to crops. The planner simply requires that the shadow prices at the extensive and intensive margins are equal, so she sets  $N'(a^*) = \theta^* = \lambda^{W^*}$  in (4.24) and uses incentives or coercion to effect the outcome (i.e. change the level of wetlands in order to satisfy this condition).

We proceed by setting the shadow value of wetlands equal to \$42/ac and solve for the base case value of wetlands that satisfy this condition, which provides a separate baseline from that in Table 4.2. Nonetheless, we then increase the marginal return to cropping by 15% (as above), and re-solve the problem so that the marginal values of the two land uses are equal. The resulting reduction in wetlands will be due to biofuel policies that increase the relative returns to cropland. By comparing the relative reduction in optimal wetlands retention under the two situations described above, we get a reasonable range of estimates regarding the potential impact of biofuels on wetlands. However, we present the results in this case only for the full PPR and not separately for each sub-region.

*Results of climate change on wetlands*

A summary of the results of climate change impacts on optimal wetlands retention and waterfowl management for the original model is provided in Table 4.6. The case where the shadow prices at the intensive and extensive margins are equated is discussed at the end of this section. Table 4.6 provides results for the entire pothole region, as well as the aggregated results for the sub-region models when aggregation is done by province and by strata. Results by individual provinces or by stratum are available tables 4.7-4.10 in the appendix to this paper. The base values from the original model (Tables 4.2, 4.4 and 4.5) are provided in Table 4.6, as are estimates of the impact of climate change on optimal management corresponding to policy scenarios 1, 1F, 2, 2F, 3 and 3F.

**Table 4.6: The Effect of Climate Change on Optimal Levels of Wetlands (W), Duck Population (D), Duck Harvest (h) and Cropped Area (a) for Different Levels of Regional Analysis**

Item	Wetlands ( $\times 10^6$ ac)	Duck population ( $\times 10^6$ )	Duck harvests ( $\times 10^6$ )	Cropped area ( $\times 10^6$ ac)
<i>Historic<sup>a</sup></i>	2.95	13.10	12.30	80.60
<i>Base-case<sup>b</sup></i>				
Entire pothole region	2.80	16.82	15.35	80.77
Province level	2.81	18.88	17.34	80.76
Stratum level	2.78	18.71	15.25	80.79
<i>1. 3°C temperature increase; no change in precipitation</i>				
Entire pothole region	2.59	15.57	14.16	80.98
Province level	2.69	18.01	16.49	80.88
Stratum level	2.69	18.33	14.34	80.88
<i>1F. 3°C temperature increase; no change in precipitation &amp; biofuel policy</i>				
Entire pothole region	1.34	8.38	7.76	82.23
Province level	1.44	9.52	9.02	82.13
Stratum level	1.45	10.43	9.65	82.12
<i>2. 3°C temperature increase; 20% decrease in precipitation</i>				
Entire pothole region	2.48	14.99	13.65	81.09
Province level	2.52	16.81	15.48	81.05
Stratum level	2.54	17.54	13.99	81.03
<i>2F. 3°C temperature increase; 20% decrease in precipitation &amp; biofuel policy</i>				
Entire pothole region	1.24	7.78	7.22	82.33
Province level	1.27	8.43	7.99	82.30
Stratum level	1.30	9.60	8.89	82.47
<i>3. 3°C temperature increase; 20% increase in precipitation</i>				
Entire pothole region	2.74	16.37	14.87	80.83
Province level	2.93	19.65	17.85	80.64
Stratum level	2.89	18.77	15.34	80.68
<i>3F. 3°C temperature increase; 20% increase in precipitation &amp; biofuel policy</i>				
Entire pothole region	1.48	9.20	8.52	82.09
Province level	1.68	11.10	10.4	81.89
Stratum level	1.64	11.56	10.73	81.93

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

In the aggregate analysis, optimal wetlands retention when there is only a 3°C increase in temperature (scenario 1) is 2.59 million acres. This represents a reduction from baseline optimal values of 8%. The optimal duck population is 15.57 million in this scenario, a reduction of about 7% from the baseline value. The optimal level of aggregate wetlands to retain when we assume that, in addition to a 3°C increase in temperature, precipitation declines by 20% (scenario 2) is 2.48 million acres, a reduction of 12% from the baseline. While these impacts are smaller than those found by Withey and van Kooten (2011) for the same scenario, the difference can be attributed to modeling differences. In particular, the wetlands state equation in this study captures the relation between wetlands and climate using a nonlinear relationship, which produces different results. Under the assumption of increased precipitation (scenario 3), the effect of climate change on wetlands is negligible, with a reduction from the baseline case of only 2%. Thus, the effects of climate change alone on wetlands may range from almost negligible to as much as a 12% reduction.

When we include the effect of policies to mitigate climate change (scenarios 1F, 2F and 3F), we find that the optimal level of aggregate wetlands to retain falls even further – to 1.34 million acres under scenario 1F (temperature only), 1.24 million ac under 2F (temperature increase and decrease in precipitation) and 1.48 million ac under 3F (increase in both temperature and precipitation). Thus, the total effect of climate change on optimal wetlands retention is a reduction of 53%, 56% and 47% for scenarios 1F, 2F and 3F, respectively. In each case, the reduction in ducks and duck harvests is roughly proportionate to the reductions in wetlands.

We can gain additional insights by examining the provincial and strata results of Table 4.6. In particular, we can determine where wetlands are likely most threatened by climate change. To do so, we focus on scenarios where warming occurs but precipitation declines. Scenarios 2 and 2F are considered in more detail because disaggregated results for scenarios 1 and 1F are similar, while there is only a minor change in optimal wetlands retention in any of the sub-regions for scenarios 3 and 3F.

Based on the provincial-level analysis in Table 4.6, the decrease in wetlands retention is 10.6% due to increased temperature and decreased precipitation (scenario 2), while the overall reduction in wetlands due to climate change and climate mitigation policies is 55% (scenario 2F). These results are similar to those based on the aggregate analysis. Climate change impacts on wetlands in the PPR are driven primarily by reductions in wetlands in Saskatchewan, which is due primarily to land use change and not climate factors per se. The relative loss in optimal wetlands area under scenarios 2 and 2F is greatest for Alberta and least for Manitoba in relative and absolute terms.

The strata level analyses reported in Table 4.6 indicate that climate factors will reduce optimal wetlands retention by 8.6% under climate scenario 2, while wetlands loss increases to 60% once the impact of biofuel policies is added to that of climate change (scenario 2F). The reduction in optimal wetlands to retain is the highest in strata 30-34 in Saskatchewan, and stratum 26 in Alberta. Further, in relative terms, wetlands loss is greatest in Alberta, and it is optimal to drain all wetlands in strata 27 and 29 located southeastern Alberta, which is drier than the rest of the prairie pothole region. In the face of a drier climate, wetlands reductions will be least in eastern parts of Saskatchewan (strata 35) and in Manitoba. While the overall level of wetlands retention should still be

highest in Saskatchewan under this ‘dry’ scenario, there should be more wetlands in Manitoba than Alberta if drier conditions prevail in the future.

#### *Discussion and further results*

We find that incentives to mitigate climate change by producing energy crops have a greater impact in reducing wetlands than the straightforward impacts of climate change itself. Hence, the overall adverse impacts of climate change on wetlands retention found in this study are much larger than those reported by Withey and van Kooten (2011). Studies that ignore the response of government to avoid climate change could significantly underestimate the effect of climate change on future values of wetlands and waterfowl.

The loss in wetlands associated with the biofuel policy is determined in large part by the change in cropland imposed through equation (4.13). Further, since there is a one-to-one relationship between wetlands and cultivated land, the results are sensitive to the estimated regression between canola prices and land entered into energy crops. The impact of climate mitigation on wetlands retention declines (increases) with a smaller (greater) projected increase in canola prices, the extent to which energy crops replace summer fallow and/or land used to grow food crops, and the potential to expand the land base by cultivating unimproved, forested lands. Therefore, the estimates provided here under the biofuel policy scenarios should be considered an upper bound of the climate effects on wetlands retention, while the direct climate effects are a lower bound.

Finally, we can re-evaluate our estimates of the effect of biofuel policies on optimal wetlands retention by equating the shadow value of wetlands to the marginal

return to cropping – setting the left-hand side of (4.24) to  $N'(a^*) = \theta^*$ . As a baseline (no climate change) solution, we obtain an optimal wetlands area of 4.70 million acres. Upon increasing the marginal net return to cropping by 15% (i.e., from \$42.00/ac to \$48.30/ac) and re-solving the model, we find that optimal wetlands retention falls to 2.97 million acres. In this case, the reduction in wetlands due to biofuel policies is roughly 35%, lower than the 45% reduction due to biofuel policies found earlier for scenario 2F. This confirms our conclusion that the effect of biofuel policies is considerable, and greater than the direct climate effects.

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

## **Conclusions**

This paper specifies a discrete bioeconomic model of waterfowl management and agricultural cropping to determine the impact of climate change on wetlands and

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

To optimize social wellbeing, the model indicates that levels of wetlands and waterfowl should be higher than historical levels. As expected, climate change is likely to reduce the socially desirable level of wetlands to retain between 35 and 56 percent from baseline values, depending on climate conditions that are expected to prevail. However, the majority of this reduction in wetlands is driven by land use change due to biofuel policies. To the extent that our disaggregation is appropriate, the results confirm those of others (e.g., Johnson et al. 2005): If future climate change leads to increased drought in the region, the focus of efforts to protect wetlands should be on the northeastern and eastern parts of the prairie pothole region.

Overall, the effect of climate change on waterfowl habitat could be severe, and agricultural policies could play a vital role in the demise of wetlands. While Withey and van Kooten (2011) consider some policy implications of this line of research, the results of the waterfowl management model presented in this paper provide two additional insights. First, the current results provide policy direction regarding where efforts should be concentrated in order to retain wetlands in the face of climate change. Second, we find that climate change adaption strategies that promote biofuel production can significantly decrease the level of wetlands retention. That in turn will reduce the greenhouse gases stored in wetlands, offsetting the CO<sub>2</sub> emission reductions due to the original biofuel

policy. The renewable fuel standard is expected to result in annual greenhouse gas emission reductions of 4.2Mt CO<sub>2</sub>, which represents a social benefit of \$84 million (assuming a price of \$20/tCO<sub>2</sub>).<sup>19</sup> Based on Cortus et al (2011), the annual climate mitigation benefits of wetlands are roughly \$14/ac, which implies a social loss of some \$17.5 million if climate mitigation incentives reduce wetlands by 1.25 million acres. Thus, the loss in wetlands could offset about 20% of the benefits of the renewable fuel standard. It is important that policies promoting energy crops also consider the costs associated with the release of greenhouse gases when wetlands are developed. Of course, possible countervailing climate-related policy mechanisms that encourage retention or creation of wetlands might offset some of these estimated effects.

One aspect missing from the current research is explicit spatial analysis. While our bioeconomic model represents a first step towards understanding how climate change impacts wetlands retention on a regional basis, limitations include assumed independence among sub-regions and an inability to treat land uses in greater detail. To address the former, it is necessary to develop a spatially explicit model that takes into account the impact of changes in wetlands in one sub-region on waterfowl production in another. Wong et al. (2012) have recently examined this issue using spatial econometrics. In terms of the current model, however, the challenge will be to develop a dynamic, spatial land use model that permits multiple activities across the landscape and takes climate uncertainty into account. This will likely require the development of a constrained

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<sup>19</sup> The potential gains due to the biofuel policy are reported in several news releases, including: [http://www.greenfuels.org/uploads/media\\_centre/2010%20news%20releases/121410\\_ethanol\\_rfs\\_starts\\_december\\_15.pdf](http://www.greenfuels.org/uploads/media_centre/2010%20news%20releases/121410_ethanol_rfs_starts_december_15.pdf).

optimization model that can be solved numerically. It might provide the richness of detail regarding the interplay between climate change, cropping incentives and protection of waterfowl habitat that decision makers often demand, but perhaps at the cost of more simple and straightforward insights.

## Appendix

**Table 4.7 (A1): The Effect of Climate Change on Optimal Levels of Wetlands (W), Duck Population (D), Duck Harvest (h) and Cropped Area (a) for Different Levels: By Province**

Scenario:	SS	1	1F	2	2F	3	3F
Alberta							
<i>W</i> (acres)	0.62	0.56	0.24	0.54	0.21	0.61	0.28
<i>D</i> (number)	4.49	4.24	2.35	4.06	2.13	4.42	2.59
<i>h</i> (number)	4.49	4.24	2.35	4.06	2.13	4.42	2.59
<i>a</i> (acres)	21.45	21.47	21.8	21.5	21.83	21.43	21.76
Saskatchewan							
<i>W</i> (acres)	1.62	1.56	0.83	1.46	0.71	1.73	0.97
<i>D</i> (number)	12.13	11.55	5.44	10.6	4.66	12.9	6.65
<i>h</i> (number)	10.51	10.03	4.94	9.29	4.23	11.12	5.95
<i>a</i> (acres)	48.16	48.27	49.01	48.38	49.13	48.11	48.86
Manitoba							
<i>W</i> (acres)	0.56	0.55	0.37	0.52	0.35	0.59	0.43
<i>D</i> (number)	2.26	2.22	1.73	2.15	1.647	2.33	1.86
<i>h</i> (number)	2.26	2.22	1.73	2.15	1.644	2.31	1.86
<i>a</i> (acres)	11.15	11.14	11.32	11.17	11.34	11.1	11.27
TOTAL							
<i>W</i> (acres)	2.81	2.69	1.44	2.52	1.27	2.92	1.68
<i>D</i> (number)	18.84	18.01	9.52	16.81	8.43	19.65	11.1
<i>h</i> (number)	17.15	16.49	9.02	15.48	7.99	17.85	10.4
<i>a</i> (acres)	80.77	80.88	82.13	81.05	82.3	80.64	81.89

**Table 4.8 (A2): Optimal Values of Wetland Acreage (W), Duck Populations (D), Duck Harvests (h) and Acreage Cropped (a), by Strata, Base Case (SS) and Total Climate Change Effect (Scenario 1F)<sup>a</sup> (millions)**

Stratum	26		27		28		29	
	SS	1F	SS	1F	SS	1F	SS	1F
W (acres)	0.36	0.19	0.1	0.02	0.08	0.04	0.08	0
D (number)	2.8	2	0.96	0.27	1.35	0.99	0.59	0
h (number)	1.73	1.65	0.81	0.23	1.15	0.84	0.51	0
a (acres)	9.48	9.65	5.11	5.21	2.12	2.16	4.73	4.81

Stratum	30		31		32		33	
	SS	1F	SS	1F	SS	1F	SS	1F
W (acres)	0.22	0.09	0.36	0.27	0.4	0.1	0.09	0.03
D (number)	1.84	0.6	1.43	1.06	2.57	0.64	0.84	0.39
h (number)	1.84	0.6	1.43	1.06	2.57	0.64	0.78	0.36
a (acres)	8.47	8.6	7.88	7.97	18.24	18.54	3.42	3.51

Stratum	34		35		36		37	
	SS	1F	SS	1F	SS	1F	SS	1F
W (acres)	0.35	0.22	0.2	0.13	0.05	0.05	0.23	0.15
D (number)	1.86	1.31	0.69	0.45	0.22	0.19	1.87	1.42
h (number)	1.81	1.28	0.47	0.45	0.16	0.16	1.44	1.4
a (acres)	6.6	6.73	3.55	3.62	0.59	0.59	3.11	3.17

Stratum	38		39		40		Total	
	SS	1F	SS	1F	SS	1F	SS	1F
W (acres)	0.04	0	0.11	0.06	0.12	0.1	2.78	1.45
D (number)	0.1	0	0.82	0.42	0.77	0.69	18.71	10.43
h (number)	0.08	0	0.63	0.34	0.72	0.64	15.25	9.65
a (acres)	3.02	3.06	2.93	2.98	1.5	1.52	80.79	82.12

<sup>a</sup> Scenario 1F models an increase in temperature of 3°C and no change in precipitation and added canola acreage to implement the renewable fuel standard. For strata 29 and 38, wetlands (W) would be zero as a result of climate change (see Figure 1 for their location).

**Table 4.9 (A3): Optimal Values of Wetland Acreage (W), Duck Populations (D), Duck Harvests (h) and Acreage Cropped (a), by Strata, Base Case (SS) and Total Climate Change Effect (Scenario 2F)<sup>a</sup> (millions)**

Stratum	26		27		28		29	
	SS	2F	SS	2F	SS	2F	SS	2F
<i>W</i> (acres)	0.36	0.18	0.1	0.02	0.08	0.04	0.08	0
<i>D</i> (number)	2.8	1.91	0.96	0.23	1.36	1.06	0.59	0
<i>h</i> (number)	1.73	1.68	0.81	0.2	1.15	0.89	0.51	0
<i>a</i> (acres)	9.48	9.66	5.11	5.21	2.12	2.16	4.73	4.81
Stratum	30		31		32		33	
	SS	2F	SS	2F	SS	2F	SS	2F
<i>W</i> (acres)	0.22	0.07	0.36	0.2	0.4	0.08	0.09	0.03
<i>D</i> (number)	1.84	0.51	1.43	0.78	2.57	0.53	0.84	0.32
<i>h</i> (number)	1.84	0.51	1.43	0.78	2.57	0.53	0.78	0.3
<i>a</i> (acres)	8.47	8.62	7.88	8.04	18.24	18.64	3.42	3.51
Stratum	34		35		36		37	
	SS	2F	SS	2F	SS	2F	SS	2F
<i>W</i> (acres)	0.35	0.2	0.2	0.12	0.05	0.05	0.23	0.17
<i>D</i> (number)	1.86	1.25	0.69	0.41	0.22	0.19	1.86	1.37
<i>h</i> (number)	1.81	1.23	0.47	0.41	0.16	0.13	1.44	1.3
<i>a</i> (acres)	6.6	6.75	3.55	3.63	0.59	0.59	3.11	3.18
Stratum	38		39		40		Total	
	SS	2F	SS	2F	SS	2F	SS	2F
<i>W</i> (acres)	0.04	0	0.11	0.05	0.12	0.09	2.78	1.3
<i>D</i> (number)	0.1	0	0.82	0.36	0.77	0.68	18.71	9.6
<i>h</i> (number)	0.08	0	0.66	0.29	0.72	0.64	15.25	8.89
<i>a</i> (acres)	3.02	3.06	2.93	2.99	1.5	1.53	80.79	82.4
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<sup>a</sup> Scenario 2F models an increase in temperature of 3°C and a decrease in precipitation of 20% and added canola acreage to implement the renewable fuel standard. For strata 29 and 38, wetlands (*W*) would be zero as a result of climate change (see Figure 1 for their location).

**Table 4.10(A4): Optimal Values of Wetland Acreage (W), Duck Populations (D), Duck Harvests (h) and Acreage Cropped (a), by Strata, Base Case (SS) and Total Climate Change Effect (Scenario 3F)a (millions)**

Stratum	26		27		28		29	
	SS	3F	SS	3F	SS	3F	SS	3F
W (acres)	0.36	0.21	0.1	0.02	0.08	0.04	0.08	0.001
D (number)	2.8	2.1	0.96	0.31	1.35	0.99	0.59	0.08
h (number)	1.73	1.65	0.81	0.27	1.15	0.84	0.51	0.07
a (acres)	9.48	9.63	5.11	5.19	2.12	2.16	4.73	4.81
Stratum	30		31		32		33	
	SS	3F	SS	3F	SS	3F	SS	3F
W (acres)	0.22	0.1	0.36	0.33	0.4	0.12	0.09	0.04
D (number)	1.84	0.74	1.43	1.31	2.57	0.8	0.84	0.42
h (number)	1.84	0.74	1.43	1.31	2.57	0.8	0.78	0.4
a (acres)	8.47	8.59	7.88	7.91	18.24	18.52	3.42	3.48
Stratum	34		35		36		37	
	SS	3F	SS	3F	SS	3F	SS	3F
W (acres)	0.35	0.24	0.2	0.15	0.05	0.05	0.23	0.18
D (number)	1.86	1.43	0.69	0.51	0.22	0.19	1.86	1.48
h (number)	1.81	1.39	0.47	0.45	0.16	0.14	1.44	1.4
a (acres)	6.6	6.71	3.55	3.6	0.59	0.59	3.11	3.17
Stratum	38		39		40		Total	
	SS	3F	SS	3F	SS	3F	SS	3F
W (acres)	0.04	0	0.11	0.07	0.12	0.1	2.78	1.64
D (number)	0.1	0	0.82	0.51	0.77	0.69	18.71	11.56
h (number)	0.08	0	0.66	0.41	0.72	0.65	15.25	10.73
a (acres)	3.02	3.06	2.93	2.97	1.5	1.52	80.79	81.93

<sup>a</sup> Scenario 1F models an increase in temperature of 3°C and an increase in precipitation of 20% and added canola acreage to implement the renewable fuel standard. For strata 29 and 38, wetlands (W) would be zero as a result of climate change (see Figure 1 for their location).

## **Chapter 5**

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

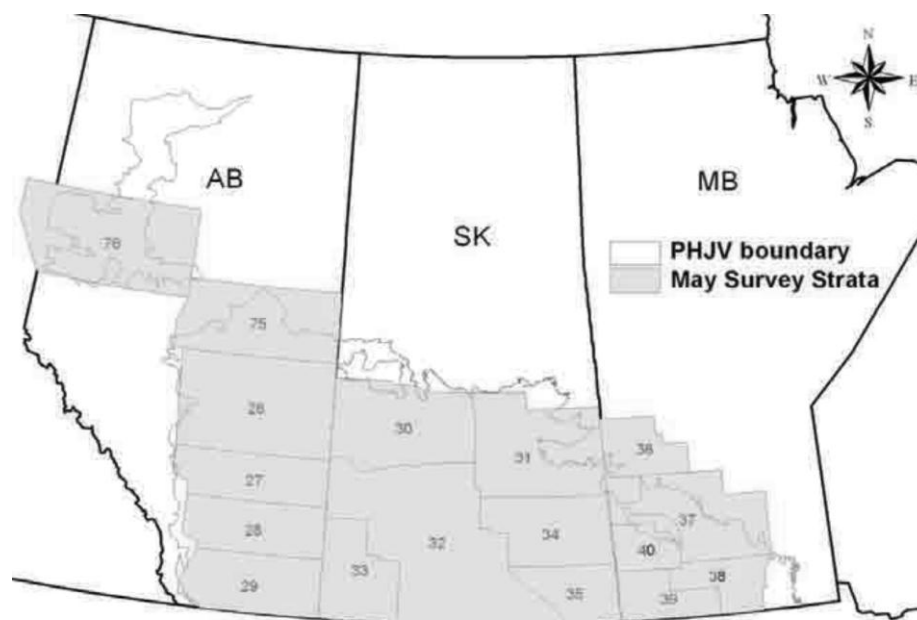
### **Introduction**

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 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 the PPR 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). Climate assessments predict that air temperatures in the region could rise by between 1.8°C and 4.0°C by 2100, and that changes in average annual precipitation during the next 100 years may vary between a decrease of 5% and an increase of 10% (IPCC 2007), although some regional assessments anticipate precipitation increases of as much as 20% but with significant decline in summer months (Ojima and Lockett 2002). To take into account potential extremes in precipitation at both ends, several studies examined the impact of climate change on wetlands 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). Wetlands are also threatened by climate mitigation policies that subsidize the production of crops for biofuels. Both climate change and policies to mitigate it could adversely affect future wetlands availability.

Given the significant benefits of wetlands in the production of migratory waterfowl (which have hunting and viewing value) and their ecosystem amenity values (van Kooten et al. 2011), it is essential that wetlands in the PPR are managed to optimize social welfare over time; it is also important to understand how climate change might impact wetlands management. Thus, the objectives of the current research are to (1) investigate the effect that projected future aridity will have on wetlands in the study region (Figure 5.1); (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; and (4) determine how a drier climate affects wetlands across the heterogeneous regions of the PPR. While the goals of this paper are very similar to those of Chapter 4, the methodology used is very different. A positive mathematical programming model is developed, which allows us to model the tradeoffs between all major land uses in the PPR as climate changes, rather than just two land uses (as in Chapter 4).



*Figure 5.1: 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 (Howitt 1995). PMP is regularly used 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.<sup>20</sup> 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). As mentioned in Howitt (2005), the PMP model was applied to the Turkish Agricultural Sectoral Model (TASM), and calibrated exactly to the base case. Howitt (2005) also states that “In European agricultural economics, the PMP calibration method has become a widely accepted standard method for agricultural economic optimization models”. He

<sup>20</sup> Model details can be found at (accessed March 15, 2011) [http://unfccc.int/adaptation/nairobi\\_work\\_programme/knowledge\\_resources\\_and\\_publications/items/5351.php](http://unfccc.int/adaptation/nairobi_work_programme/knowledge_resources_and_publications/items/5351.php).

provides a list of 40 published papers using the PMP methodology. Many studies that use PMP to examine the impact of environmental policies in the European Union on the agricultural sector can be found in Gohin 2000 and De Frahan 2007). Finally, Heckeley and Britz (2005) also provide a review of models that employ PMP. Yet, despite the rapid ascent of the PMP methodology, to our knowledge, no studies use PMP to model land use change in the context of wetlands management.

In this regards, Brown and his colleagues (Brown and Hammack 1973; Hammack and Brown 1974; Brown et al. 1976) were the first to use mathematical bioeconomic models to address wetlands conservation. 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 uncertainty, 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 explicitly to model the tradeoffs between agricultural production and wetlands management. We use the PMP method to calibrate separate models for each of strata 26-40 used by the U.S. Fish and Wildlife Service's Population Survey (Figure 5.1). 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 sums private returns (wetlands represent a cost) and public returns (positive social benefits). In addition to base-case results, we estimate how a warmer, drier future climate will induce changes in crop yields and impact land use. We focus on the case of a warmer climate with decreased precipitation, but discuss the effects of alternative scenarios in the results section. We also estimate how higher returns to canola will impact land use; higher returns to canola represent a policy-induced increase in the demand for biofuels.

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 34% 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.

We proceed in the next section by specifying our land use model and the positive mathematical programming approach. We then use regression analysis to provide an estimate of the impact that climate change will have on crop yields and wetlands. This is

followed by a discussion of the four scenarios we investigate and the changes in land use and wetlands retention predicted by our land use model. Some policy implications are considered in the concluding section.

## **Analytic Model**

### *Positive mathematical programming model*

Positive mathematical programming 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. It also captures land quality heterogeneity and the fact that land suitability varies across space for a given crop. Calibrated 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. First, an LP is solved that maximizes net returns to land uses, subject to resource and calibration constraints:

$$\text{Max} \quad \sum (p_i y_i - c_i) x_i \quad (5.1)$$

$$\text{s.t.} \quad \sum a_{ji} x_i \leq \bar{R}_j, \forall j \quad (5.2)$$

$$x_i \leq x_i^o + \varepsilon_i, \forall i \quad (5.3)$$

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  $\bar{R}_j$  is the total amount of resource  $j$  that is available. Much like the CRAM model, we consider only the land resource so that  $a_{i,\text{land}} = 1$  for all  $i$ .<sup>21</sup> The calibration constraints (5.3) are needed to implement PMP, where  $x_i^0$  are the observed areas in each land use and  $\epsilon_i$  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 use activities.

Dual values from the LP described by (5.1), (5.2) and (5.3) are then used in the second stage of the calibration to estimate the parameters of the yield function for each crop in each region. Assuming a quadratic yield function,  $y_i = (\beta_i - \gamma_i x_i) x_i$ , the dual values on the calibration constraints,  $\lambda_{2i}$  in equation (5.3), are equal to the difference between the value of the average and marginal products of land, VAP and VMP, respectively. Thus,  $\gamma_i$  and  $\beta_i$  are derived as follows:

$$\lambda_{2i} = \text{VAP}_i - \text{VMP}_i = p_i(\beta_i - \gamma_i x_i) - p_i(\beta_i - 2\gamma_i x_i) = p_i \gamma_i x_i \quad (5.4)$$

$$\gamma_i = \frac{\lambda_{2i}}{p_i x_i} \quad (5.5)$$

$$\beta_i = y_i + \gamma_i x_i \quad (5.6)$$

Given the dual values for each calibrated land use ( $\lambda_2$ ) and data on  $p$ ,  $y$  and  $x$ , we can calibrate nonlinear yield functions that represent land owners decisions in a given region.

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<sup>21</sup> Information based on discussions with AAFC staff. Unlike the current application, the CRAM model considers a water resource constraint in addition to land constraints.

The perturbation coefficient  $\varepsilon_i$  in equation (5.3) decouples the shadow prices for equations (5.2) and (5.3), and enables the dual values from equation (5.3) 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, where the calibration constraint does not bind and the activity is constrained only by the land use equation (5.2).<sup>22</sup> When  $\lambda_{2i}$  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  $\gamma_i = 0$ . 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 ( $\lambda_1$ ) in producing the marginal crop. For the first-order conditions to hold, a decrease in  $\lambda_1$  will be offset by an increase in the value of  $\lambda_2$  for the marginal crop.<sup>23</sup> This new value of  $\lambda_2$  for the marginal crop,  $\bar{\lambda}_{2,marginal}$ , can be used to calculate the nonlinear yield function for the marginal activity. All other  $\lambda_{2i}$  values must be adjusted by  $\bar{\lambda}_{2,marginal}$ .

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<sup>22</sup> Recall that, in the current application, we have only one equation in (5.2), namely, a land constraint, so  $a_{i,land} = 1$ , and there is only one shadow price,  $\lambda_1$ .

<sup>23</sup> See Howitt (1995, p.337) for more detail and an example.

In the third step, the PMP problem becomes:

$$\text{Maximize } \sum [\rho_i(\beta_i - \gamma_i x_i) - c_i] x_i \quad (5.7)$$

$$\text{s.t. } \sum a_i x_i \leq \bar{R} \quad (5.8)$$

$$x_i \geq 0 \quad (5.9)$$

This model uses the calibrated yield function from the second stage to represent the landowners' decisions. Using only the resource constraint (5.8) and non-negativity constraints (5.9), the solution replicates the observed allocation for a base year. For different scenarios (discussed below), only the parameters in (5.7) need to be adjusted.

#### *Treatment of wetlands and pasture land*

For all crops included in this paper, data are available for prices, yields, variable costs and observed acreage. For wetlands and pasture land, the land that is most suitable waterfowl habitat, data exists for observed acreage but not the other variables. To include these land uses in the model, we need to specify net revenues by region for these activities. This section outlines the theoretical treatment of wetlands and pasture land; more detail on the actual values used in this study is provided in the next section.

First, from a land use standpoint, pasture land provides benefits to farmers as an intermediate land use: pasture provides benefits via livestock. Since we do not include livestock in this model, we must simply assume the value to farmers of having land in pasture.

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 Woodward 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 5.1.

**Table 5.1: 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 al. 2010) to \$150 per acre (Brander et al. 2006). These benefits should be considered, since the loss of wetlands will come at a cost to society. This study will consider how the inclusion of these benefits will impact land use change due to climate change. The model is first solved from the social planners' perspective, where wetlands are determined to have benefit to society. The value of wetlands used in this study is discussed in the next section. For comparison, the model is solved for the private landowner, where wetlands represent a net cost to landowners in terms of foregone agricultural production.

## Data

To solve the land use model, we require observed acreage ( $x$ ), yield ( $y$ ), price ( $p$ ) and variable cost ( $c$ ) data for each stratum and each land use. We want to calibrate our model to the most recent year for which data are available because of ongoing changes in agriculture policy and global warming. Since our data come from the latest Census of Agriculture (Statistics Canada 2007), the most recent year for which the data are available is 2006. Acres seeded by major crops in the Prairie Provinces in 2006 as well as historic averages are provided in Table 5.2.<sup>24</sup> 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. In the remainder of this section, we discuss data sources for the crops used in the model (spring wheat, winter wheat, barley, oats, dry field peas, canola and hay) and then how wetlands and pasture are treated. Data used to calibrate the constrained LP model and the nonlinear yield functions of the previous section are presented in Tables 5.3 through 5.6, all pertaining to the base year of 2006. In Tables 5.3 through 5.6, data are provided for each stratum and for each crop for observed acreage, yield, price and variable costs, respectively. Strata 26-29 represent regions in Alberta, strata 30-35 are regions in Saskatchewan and strata 36-40 are in Manitoba.

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<sup>24</sup> Data are from Cansim Table 001-0017.

**Table 5.2: Agricultural Land use in the Canadian Prairie Provinces ('000s ac)**

	Spring Wheat	Winter Wheat	Oats	Barley	Field 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

**Table 5.3: Observed Acreage in Each Land Use ('000s ac)**

Stratum	Spring wheat	Winter wheat	Barley	Oats	Dry Peas	Canola	Hay land	Wetland	Tame Pasture
26	1638.1	5.4	1256.4	438.7	170.8	1598.9	1657.0	458.8	2062.0
27	1304.0	12.3	823.6	161.8	84.1	532.9	858.1	140.4	866.2
28	539.1	6.0	503.5	41.5	82.9	220.1	379.9	145.0	321.8
29	873.9	89.6	684.9	47.9	120.5	181.0	381.4	102.2	695.5
30	1751.5	4.3	1048.7	716.7	483.5	2189.5	1287.0	387.7	873.7
31	1072.5	22.0	755.8	626.4	249.3	1907.9	870.9	530.6	616.0
32	3018.7	53.5	997.1	433.2	1144.9	1097.4	1577.0	541.4	1622.8
33	403.0	15.8	183.6	64.6	224.1	57.6	382.3	74.5	639.1
34	1117.7	41.1	541.5	486.3	239.0	947.8	695.9	555.8	618.9
35	602.9	22.4	232.0	198.7	116.7	401.5	423.9	221.2	380.1
36	15.9	0.00	13.7	22.6	0.0	175.1	135.7	65.5	78.1
37	427.6	24.9	211.9	214.6	4.4	503.0	930.0	223.1	455.4
38	827.4	55.1	164.7	281.3	6.0	563.5	298.5	50.2	136.9
39	723.9	42.0	231.8	176.3	41.5	539.1	407.7	158.0	308.2
40	310.1	12.3	150.5	109.8	25.2	342.5	265.9	127.8	142.9

**Table 5.4: Yields (bushel/ac for crops; ducks per ac for wetlands)**

Stratum	Spring wheat	Winter wheat	Barley	Oats	Dry Peas	Canola	Hay land	Wetland (social)	Wetland (private)
26	45.00	45.00	57.00	75.00	35.00	35.00	60.00	5.18	0
27	42.60	42.60	55.40	65.90	35.00	34.60	1.76	5.37	0
28	43.00	43.00	60.70	66.10	35.00	34.90	2.25	6.14	0
29	43.00	43.00	60.70	66.10	35.00	34.90	2.25	5.53	0
30	37.72	32.50	55.30	74.55	38.75	32.06		5.43	0
31	35.98	28.30	54.68	71.85	31.47	29.63		3.92	0
32	28.64	42.10	44.48	47.81	30.95	24.45		6.87	0
33	23.68	35.25	42.46	56.82	20.08	14.90		5.00	0
34	32.04	39.83	51.58	60.74	30.15	27.50		2.07	0
35	28.98	43.73	47.10	48.72	27.60	22.00		3.04	0
36	56.20	na	69.90	90.10	na	44.40		0.81	0
37	51.90	51.90	68.30	88.50	43.00	40.50		1.84	0
38	58.70	58.70	80.40	108.60	46.30	45.90		3.00	0
39	40.60	40.60	54.30	68.30	36.50	31.50		4.32	0
40	51.00	51.00	72.60	110.00	38.00	40.50		4.04	0

**Table 5.5: Price (\$/bushel for crops; \$/duck for wetlands)**

Stratum	Spring wheat	Winter wheat	Barley	Oats	Dry Peas	Canola	Hay land	Wetlands (social)	Wetlands (private)
26-40	4.23	4.23	2.88	2.55	3.99	7.4	1.3	2	0

**Table 5.6: Variable Costs (\$/ac)**

Stratum	Spring wheat	Winter wheat	Barley	Oats	Dry Peas	Canola	Hay land	Wetland (social and private)
26	141	141	134	138	135	240	55	5
27	141	141	134	138	135	240	55	5
28	103	107	123		107	162	35	5
29	103	107	123		107	162	35	5
30	119	119	109	148	108	149		5
31	119	119	109	148	108	149		5
32	109	109	106		103	143		5
33	99	99	94	91				5
34	119	119	109	148	108	149		5
35	119	119	109	148	108	149		5
36	154	146	137	122	143	194		5
37	154	146	137	122	143	194		5
38	154	146	137	122	143	194		5
39	154	146	137	122	143	194		5
40	154	146	137	122	143	194		5

*Data sources for crops*

All observed acreage data in Table 5.3 (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 the data by Stratum from the US Fish and Wildlife Service Waterfowl Population Survey. 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 in Table 5.4 come from the governments of Alberta, Saskatchewan and Manitoba. For strata 26-29, we use the Government of Alberta's AgriProfit\$ Benchmark

Analysis.<sup>25</sup> Yields for each major crop are provided by soil region. For strata 30-35, the Government of Saskatchewan provides yields by crop for each rural municipality (RM).<sup>26</sup> The RM data are aggregated to the stratum level to obtain the yield data per stratum. For strata 36-40, yield data in Manitoba are provided by crop and by risk area, which we match to each stratum.<sup>27</sup> We also require historical data for crop yields when we estimate the climate-crop regression equation (5.15) specified below. For Alberta and Manitoba, historical data were obtained through correspondence with relevant individuals in the respective agricultural ministries of these provinces.<sup>28</sup> In Saskatchewan, historic yield data by crop are available from their website (as indicated above).

In Table 5.5, for all 7 crops, price data come from Statistics Canada (Cansim Table 002-0043) and variable cost data in Table 5.6 come from the three provincial governments in the PPR. For strata 26-29, data come from the same source as the yield data. For strata 30-35, operating costs come from crop planning guides published by region by the Government of Saskatchewan.<sup>29</sup> For strata 36-40 (Manitoba), operating costs are only available for the whole province; these values are assumed the same for all strata<sup>30</sup>.

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<sup>25</sup> [http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/econ10237](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/econ10237) (accessed March 15, 2011).

<sup>26</sup> <http://www.agriculture.gov.sk.ca/rmyields> (accessed March 15, 2011).

<sup>27</sup> <http://www.gov.mb.ca/agriculture/crops/cropproduction/gaa01d27.html> (accessed March 15, 2011).

<sup>28</sup> For Alberta, the most recent data are found at: [http://www1.agric.gov.ab.ca/\\$department/deptdocs.nsf/all/sdd12891](http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12891). (accessed on March 15, 2011).

<sup>29</sup> <http://www.agriculture.gov.sk.ca/crop-planning-guides> (accessed March 15, 2011).

<sup>30</sup> <http://www.gov.mb.ca/agriculture/financial/farm2005/cac40s01.html> (accessed March 15, 2011).

*Data sources for 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: 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. 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 (Tables 5.4 through 5.6); 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 that the value to farmers, regardless of region, is much less than the net revenue to cropland. We assume a value of \$20 per acre. The base case model will calibrate to 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 et al. (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, where 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 model solution is to the assumed value of wetland benefits. The value of wetlands to both the private landowner and society 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 nuisance cost of providing wetlands (i.e., the disruption of farm activities). From Cortus et al. (2011) and van Kooten et al. (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. 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, production of waterfowl, and so on (Brander et al. 2006, p.226). Cortus et al. (2010) adapt estimates from Belcher et al (2001) of the social benefit of wetlands in an area of Saskatchewan. The estimates range between \$16 and \$51 per acre with a 'best

guess' of \$32/ac. Further, mean values of wetlands are reported as \$60 per acre in North America in Brander et al. (2006). We choose \$35 per acre for the social value of wetlands in this study. This is based on the best guess of Cortus et al (2010), which is likely the most accurate estimate for the PPR since their estimate is for a region in the PPR.

To account for variation in wetland values across strata, we estimate how the value of wetlands varies in terms of the production of waterfowl. 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. 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 to 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.<sup>31</sup> 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.

### *Data trends*

Overall, several patterns are discernable in the data presented in Tables 5.2 through 5.5. Generally, oats and canola are the most profitable cropping activities in the PPR, followed by barley and wheat. Peas and hay land are the least profitable. When considering only the private costs of retaining wetlands, wetlands incur a loss; however, when considering the social benefits, wetlands can provide as much benefit as certain crops. Of all the crops, canola and spring wheat have the largest acreage, with hay land

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<sup>31</sup> Hammack and Brown (1973) estimated a value to hunters of \$3 per duck; the estimate from van Kooten et al. (2010) includes amenity values of ducks, and is around \$9.

the third highest. Barley and pasture land also constitute significant land use. While acres in wetlands tend to be lower, it is roughly equivalent to acres in oats, and higher than acres in winter wheat or peas.

## **Climate Change**

### *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; Schlenker et al. 2006). Alternatively, detailed crop-growth models, such as EPIC, CERES and CROPGRO, have been employed to 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 use in this study because neither provides the level of disaggregation required for this study (in the PPR). The Ricardian approach does not provide specific estimates of crop yields, which are needed for our purposes, while the use of crop-growth models is beyond the capacity of the current study as such models require information unavailable to the current authors. 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:

$$y_{it} = \gamma + \beta X_{it} + \varepsilon_{it} \quad (5.10)$$

where  $y_{it}$  represent the dependent variable,  $\gamma$  is the intercept term,  $\beta$  is a K-dimensional column vector of parameters to be estimated,  $X$  is a K-dimensional row vector of explanatory variables, and  $\varepsilon_{it}$  are the error terms. A common assumption in panel models is that:

$$\varepsilon_{it} = v_i + u_{it} \quad (5.11)$$

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

Panel models can take the form of fixed effects (FE) or random effects (RE), depending on assumptions about the individual-specific effects. In the FE model, the individual-specific effect is a random variable that is allowed to be correlated with the explanatory variables. Including specification (5.11) and rewriting (5.10), the FE model is:

$$y_{it} = (\gamma + v_i) + \beta X_{it} + u_{it} \quad (5.12)$$

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.

The RE model is different since the regional-specific effect  $v_{it}$  are random variables that are no longer time invariant, uncorrelated with the explanatory variables and randomly distributed across units. The RE model is written as:

$$y_{it} = \gamma + \beta X_{it} + v_{it} + u_{it} \quad (5.13)$$

where the two error components are independent of each other:

$$u_{it} \sim i.i.d. N(0, \sigma_u^2) \text{ and } v_{it} \sim i.i.d. N(0, \sigma_v^2) \quad (5.14)$$

Here  $v_{it}$  represents the between-region errors and  $u_{it}$  the within-region errors.

A FE panel regression model is used in the current context to estimate the impact of precipitation and temperature on average crop yields for each crop in each stratum:

$$y_{rit} = \beta_0 + \beta_1 T_{it} + \beta_2 P_{it} + \beta_3 time + d_i + u_{it}, \quad (5.15)$$

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  $t$ ;  $time$  is a time trend included to capture technological change;  $d_i$  are region specific dummies that capture the fixed effects, or the unobserved variables that affect yields differently by region;  $\beta$ s are parameters to be estimated; and  $u_{it}$  are error terms. The individual specific effects capture unobserved heterogeneity across strata, such as input prices, soil characteristics and farmers' preferences, and, therefore, the  $\beta$ s provide unbiased estimates of the effect of climate on crop yields.

To estimate the impact of climate change on land use in equation (5.15), 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 15 regions and a time series of 54 years for each crop. The source of these data is discussed in the earlier data section.

Precipitation and temperature data come from Environment Canada's historical weather information, found in the National Climate Data and Information Archive.<sup>32</sup> 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 the precipitation (especially as snowfall) during the period between fall harvest and spring planting is important to crop growth in a region where significant parts have historically been characterized by drought.

For each of the seven equations, we tested for redundant period FEs using an F-test. In each case, we strongly reject the null hypothesis, 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 reject 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 (5.15) is estimated for each of the crop activities and wetlands using panel fixed effects.

We use the dummy variable approach to account for fixed effects – for unobserved heterogeneity across regions. The result is that 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

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<sup>32</sup> [http://www.climate.weatheroffice.gc.ca/Welcome\\_e.html](http://www.climate.weatheroffice.gc.ca/Welcome_e.html) (accessed March 15, 2011)

and precipitation. Whether or not these variables are statistically significant will reveal if the effect of temperature and precipitation varies across region.

Regression results are reported in a table in the Appendix. Generally, the models perform quite well, with relatively high  $R^2$  values and most estimated coefficients having the expected signs. 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 the Table. For wetlands, only the effect of temperature varies by region, and therefore estimates of the interaction variables (temperature and regional dummies) are reported in the Table for wetlands. Results 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 IPCC 2007; Brklacich et al. 1999).

#### *Climate scenario description*

To determine the impact of climate change on wetlands in the PMP model, we assume an increase in temperature of 3°C and a decrease in precipitation of 10% (see

Larson 1995; Johnson et al. 2005; Sorenson et al. 1998; Withey and van Kooten 2011).<sup>33</sup>

While Johnson et al. (2005) also consider the case where precipitation increases under climate change, we focus on the more interesting situation where there is a potential increase in future aridity. To some extent, this might be somewhat representative of the prolonged droughts that characterized the region during the early 1600s, late 1700s and mid-1800s.<sup>34</sup> However, we also note the implications for a wetter climate in the results section.

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 make no adjustments to input use as a result of a hotter and drier climate; for example, we do not permit farmers to 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 a Table in the Appendix and are provided for each stratum in Table 5.7. Values in the table represent a decrease from the historic average measured in bushels per acre. For most crops in Table 5.7, 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 there is a marginally positive impact of climate on canola yields.

The direct effect of climate change on wetlands area occurs because a warmer and

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<sup>33</sup> Although projections from regional climate models could be used, this would add unnecessary complexity; further, predictions from climate models are considered to lack scientific validity (Green and Armstrong 2007; Pielke and Wilby 2012). Our approach is reasonable because, if temperatures increase, the increase is likely to be relatively uniform, but the absolute change in precipitation, which plays a more important role, will vary across strata.

<sup>34</sup> See article on Drought in the Encyclopedia of Saskatchewan, A Living Legacy at (accessed February 28, 2012): <http://esask.uregina.ca/entry/drought.html>.

drier climate simply leads to fewer wetlands. We can use the regression results for wetlands area (as opposed to yield)(see Table in Appendix), to predict the percent change in wetland area in each sub region under the future climate. Table 5.7 reveals that wetlands will be dramatically reduced due to warmer, drier conditions; the average reduction across regions is 34.8 percent, with losses the highest in Saskatchewan.

There is also an indirect effect associated with the reduction in wetlands. 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 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. Then, 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 sub region 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, namely, Canada'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 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 15%. 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, plus the indirect effect associated with the increased price of canola due to mitigation policy.

Finally, scenario #4 is the same as the 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.

**Table 5.7: Change in Crop Yields and Wetlands Area due to 3°C Higher Temperatures and 10% Lower Precipitation, % Change by Stratum<sup>a</sup>**

Stratum	Wheat	Barley	Oats	Canola	Dry peas	Wetlands	Hay land
26	-6.62	-6.38	-6.91	3.51	-3.74	-20.42	4.50
27	-7.73	-6.67	-7.39	3.48	-3.41	-23.93	4.72
28	-7.12	-5.80	-6.71	3.62	-3.83	-18.07	4.67
29	-8.48	-7.07	-8.51	2.52	-3.92	-37.78	2.93
30	-7.83	-6.68	-7.07	3.87	-3.77	-37.13	6.40
31	-7.86	-6.93	-7.29	3.67	-4.12	-42.67	5.21
32	-9.11	-7.56	-8.36	4.60	-3.56	-49.02	7.79
33	-9.76	-8.02	-8.10	4.92	-3.22	-44.59	7.26
34	-8.45	-7.08	-7.82	3.71	-3.34	-51.12	4.78
35	-9.74	-8.27	-9.02	4.32	-3.16	-50.12	5.81
36	-8.19	-7.63	-9.03	2.54	-3.16	-26.59	5.81
37	-7.86	-7.30	-8.33	3.25	-3.74	-31.37	5.81
38	-5.15	-10.25	-7.74	2.58	-3.74	-18.41	5.81
39	-9.65	-8.07	-9.37	3.97	-3.74	-33.41	5.81
40	-7.69	-6.55	-7.19	3.18	-3.74	-38.42	5.81

<sup>a</sup> Projections based on the estimated coefficients in Appendix Table.

## **Results**

### *Results of PMP model (base case)*

In this section, 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 using the CPLEX and CONOPT3 solvers. Parameter values for the nonlinear yield functions that were estimated and used to solve the PMP model are provided in Table 5.8, while Table 5.9 presents the PMP modeling results. We provide the areas in each of the eight possible agricultural activities (various crops) and wetlands for the PMP base-case replication of the observed land uses. As seen in Table 5.9, the model calibrates almost exactly to observed 2006 levels, indicating that the PMP method performs well and is suitable for policy analysis.

**Table 5.8: Nonlinear Yield Parameters**

	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

**Table 5.9: Observed (2006) Land Uses and PMP Model Base Case Results ('000s ac)**

Scenarios	Spring			Winter		Dry peas	Wetland area	Hay land	Pasture
	wheat	Barley	Oats	wheat	Canola				
Observed	14,626	7,800	4,020	407	11,258	2,993	3,782	10,551	9,059
PMP Base	14,621	7,807	4,019	409	11,270	2,975	3,786	10,563	9,033

In addition to the results provided in Table 5.9, shadow values of the land resource constraint ( $\lambda_1$ ) 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,  $\lambda_2$ . Wheat is a marginal crop in two 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.

#### *Climate effects on land use*

##### *Social planner vs. private landowner*

Table 5.10 compares land use from the PMP model base case to each of the four climate scenarios that we identified in the previous section. The bottom five rows of Table 5.10 provide the optimal land use allocations under each of the four scenarios identified above. 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 wetlands retention under a new climate regime if they are privately managed or managed to take into account social benefits.

**Table 5.10: Land Uses under PMP Model Base Case and Climate Change Scenarios ('000s ac)**

Scenarios <sup>a</sup>	Spring wheat	Barley	Oats	Winter wheat	Canola	Dry 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	14,621	7,807	4,019	410	11,270	2,975	3,786	10,563	9,033
#1	12,198	6,126	3,610	344	13,062	2,682	4,012	11,792	10,428
#2	12,285	6,173	3,623	345	13,100	2,734	2,575	11,847	10,727
#3 (social)	11,888	5,655	3,577	342	16,743	2,606	2,496	11,402	9,691
#4 (social)	11,028	5,820	3,581	342	16,893	2,850	2,715	11,506	9,675
#3 (private)	12,096	5,846	3,606	345	16,898	2,688	570	11,594	10,420

<sup>a</sup> For scenario #1, we employed the projected yield data provided in Table 5.7. For scenario #2, we added an adjustment provided by the calibrated marginal yield parameter for wetlands (see Table in Appendix); the marginal yield parameter was adjusted because there is no 'yield' from wetlands that is impacted by climate. Finally, to estimate the impact 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.

Several trends are discernable from the climate change effects in Table 5.10. First, in terms of cropland, the changes modeled under scenario #1 suggest that a warmer climate has the most pronounced negative effect on spring wheat production, although reductions in plantings of barley, oats and peas are similar. The only crops that experience a positive effect are canola and hay. This is not surprising given the yield changes expected as a result of climate change (see Table 5.7). Canola planting might increase by more than 15% as a result of climate change, but plantings are boosted by another 30% or so when biofuel policies increase the price of canola.

Wetlands area is projected to increase by about 6% due to the decreased 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 a total of 32%, with 38% 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 on wetlands (scenario #3) is minimal, increasing the overall effect from a reduction in wetlands of 32% to a reduction of 34%. 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 to 28%.

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 2011a, 2011b). 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 6% 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, the reduction of wetlands is roughly projected to be 28-34% from current levels. However, if a private landowner ignores the externality effects of converting wetlands to cropland, wetlands area falls by about 85% from that observed 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.

*Regional climate effects*

The percentage changes in land allocation are provided in Table 5.11 for each of the fifteen strata, but only for scenario #3, where the private landowner is incentivized to take into account the social values of wetlands. A summary of the reduction in wetlands under this same scenario is provided in Table 5.12. Results confirm those of Table 5.10. The largest increase in land use triggered by predicted global warming is in canola, 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.

**Table 5.11: Change in Land Use from Base Case by Stratum, Scenario #3 using Social Benefits of Wetlands (%)**

Strata	Spring wheat	Barley	Oats	Winter wheat	Canola	Dry peas	Wetlands	Hay land	Pasture
26	-25.8	-53.6	-13.1	-25.1	118.5	-100.0	-8.8	-7.0	-20.5
27	-23.1	-47.8	-12.3	-25.3	138.5	-100.0	-23.1	8.0	2.7
28	-9.5	-14.3	-12.6	-10.3	20.9	-9.5	-14.9	7.6	26.1
29	-11.3	-17.5	-16.1	-12.2	19.4	-8.7	-34.7	8.2	31.5
30	-27.5	-16.1	-11.2	-17.6	22.3	-5.8	-34.2	12.9	27.6
31	-27.4	-16.7	-12.8	-9.9	27.2	-32.1	-39.8	11.3	28.8
32	-5.0	-18.1	-7.5	-9.1	45.0	3.8	-45.1	15.7	20.9
33	-16.3	-23.4	-8.7	-32.5	23.4	-5.4	-44.6	7.2	0.0
34	-5.0	-5.7	-12.8	-9.3	33.6	33.3	-44.4	14.9	30.5
35	-17.2	-31.2	-15.8	-29.7	93.7	-52.9	-50.6	5.0	-1.8
36	-16.8	-19.7	-9.2	-49.0	15.2	-5.4	-26.8	5.8	-1.2
37	-20.0	-18.8	-8.3	-16.6	20.1	-22.1	-29.9	7.2	10.4
38	-8.2	-16.4	-6.3	-7.3	14.2	-11.9	-15.9	7.9	16.3
39	-98.6	-80.9	-9.7	-42.2	49.9	-96.0	-29.5	9.1	13.3
40	-13.5	-8.3	-4.9	-11.4	19.3	-55.1	-34.2	10.0	17.3
Total	-18.7	-27.6	-11.0	-16.5	48.6	-12.4	-34.2	8.0	7.3

**Table 5.12: Reduction in Wetlands by Stratum, Scenario #3 using Social Benefits of Wetlands ('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	419	108	124	67	256	320	297	41	309	109	48	157	42	112	84	2493

The loss in wetlands across regions in the PPR ranges from about 9% to nearly 51% (Table 5.11), or 8000 to 248,000 acres (Table 5.12). Unsurprisingly, the effect of climate change and mitigation policies on wetlands is not homogenous across regions, because precipitation and soil characteristics (which impact crop yields) differ dramatically across the study region. In Table 5.11, the largest proportional declines in wetlands are in strata 29, 30-35 and 40, while the largest decreases in wetlands area (Table 5.12) are in strata 31, 32 and 34. Thus, wetlands loss is greatest in percentage terms in southern Alberta (stratum 29), southern Saskatchewan (strata 32, 33, 34 and 35), and south western Manitoba (stratum 40).

Recall that, 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 5.7. 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 as a result of 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 5.11 and 5.12. In doing so, it is helpful to consult Figure 5.1.

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, 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 5.12); 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 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 15%, which is the smallest proportional loss of wetlands in 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 in the PPR.

Finally, the overall projected reduction in wetlands in Manitoba is 29%, which is smaller than that in the other provinces. The proportional loss of wetlands is the smallest in eastern and northern strata (36-38), whereas the south western strata are the most susceptible to climate change, with losses above regional averages.

## **Discussion**

Positive mathematical programming was used 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 15 regions and nine land uses per

region was used to project a reduction of wetlands by some 28-34% from observed 2006 levels as a result of a warmer and drier climate. If the externality benefits of wetlands are ignored, however, the effects of climate on wetlands are even more severe, with as much as 85% of current wetlands in the region potentially being lost.

The impact of climate change on wetlands will not be homogenous 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 northern regions of Saskatchewan and Alberta. In our models, the warming-induced shift in wetlands in Canada's pothole region is toward 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 21<sup>st</sup> century.

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 the externality benefits of wetlands are to be 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.

## Appendix

**Table 5.13 (A1): Estimated Parameter Estimates for Climate Equation (5.15)**

Variable	Wheat <sup>a</sup>	Barley	Oats	Canola	Dry Peas <sup>b</sup>	Wetlands	Hay land <sup>b</sup>
Constant	16.92**	21.19**	23.92**	3.91**	11.81**	388212.9**	0.319
Temperature	-0.51**	-0.62**	-0.72**	0.416**	-0.17	-24954.6**	0.042*
Precipitation	0.019**	0.027**	0.043**	0.012**	0.007*	46.53	0.0014**
Time	0.35**	0.54**	0.56**	0.29**	0.398**		0.005**
Strata dummy variables multiplied by temperature							
Stratum27						16755	
Stratum28						20506.9*	
Stratum29						15463.2	
Stratum30						-3653.2	
Stratum31						-29215**	
Stratum32						-44199.1**	
Stratum33						11656.8	
Stratum34						-38765.8**	
Stratum35						-12095.1	
Stratum36						20541.4*	
Stratum37						775.2	
Stratum38						23117*	
Stratum39						11382.2	
Stratum40						8429.1	
Adjusted R <sup>2</sup>	0.63	0.60	0.50	0.54	0.28	0.77	0.30
Observations	762	772	777	696	301	779	239

Notes:

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

<sup>a</sup> Historic data on winter wheat were not available, so this regression is used for both spring and winter wheat

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

## **Chapter 6**

### **Conclusion and Policy Discussion**

Wetlands are rich ecosystems that provide a range of benefits to society. However, these benefits do not go to the landowners (farmers) who support wetland ecosystems, leading to a positive externality. Therefore, it is not surprising that wetlands in the Prairie Pothole Region of Canada have historically, and continue to be drained in favour of agricultural development. Wetlands are also impacted by environmental conditions, as warmer and drier conditions will lead to the evaporation of wetlands. In addition to the economic incentives that lead to drainage, wetlands are also threatened by climate change, if a warmer and drier climate prevails in the 21<sup>st</sup> century.

This dissertation studies the optimal management of wetlands (and the waterfowl they support) under uncertain future conditions. We use bioeconomic modeling and land use modeling to estimate how wetlands should be managed to maximize social welfare and how wetlands may be affected by climate change. This research begins by extending an existing bioeconomic model of optimal duck harvest and wetland retention to include the nonmarket (in situ) value of waterfowl and the ecosystem service and other amenity values of wetlands. The research then adapts the model to estimate the effect of climate change on optimal wetlands management, focusing solely on direct climate effects and limiting the analysis to the entire PPR. In the third and fourth papers, the research uses two separate methodologies to estimate the effect of climate change on wetlands, as well as the effect of biofuel policies that aim to reduce green house gases. These analyses are conducted for spatially disaggregated regions of the PPR. In the third paper, the earlier

bioeconomic model is extended to include cropping decisions. The fourth paper develops a multi-region Positive Mathematical Programming model that calibrates land use in the PPR to observed acreage in 2006.

Results from each of the first three papers (Chapters 2-4) indicate that to maximize social welfare, wetlands, ducks and duck harvests need to be increased relative to historical levels. Further, in the face of climate change, results from bioeconomic modeling indicate that optimal wetlands retention could be reduced by between 35 and 56 percent from optimal levels. From Chapter 3, the reduction in wetlands due to climate change alone is as much as 38 percent from the baseline climate. The direct climate effects in Chapter 3 are greater than those in the model of Chapter 4 but consistent with those in Chapter 5. This is because in Chapters 3 and 5, linear regression is used to estimate the impact of climate variables on wetlands, whereas nonlinear regression is used in Chapter 4. This result shows that functional form can play a crucial role in this analysis. In Chapter 4, the total climate change effect, including the effect of biofuel policies to mitigate climate change, is a reduction of wetlands by 35-56 percent from historic levels, with the majority of this change due to land use change. Wetlands loss is geographically heterogeneous, with losses being the largest in Saskatchewan. In Chapter 5, results of the PMP model indicate that climate change could decrease wetlands in this area by as much as 34 percent (if the social benefits of wetlands are internalized). However, unlike Chapter 4, most of the change is due to climate rather than land use change. The climate effect is larger due to the linear regression model, whereas the impact of land use changes on wetlands is smaller due to the fact that all land uses are accounted for and there is substitution between crops when canola prices rise. In Chapter

4, there was only substituting between ‘all crops’ and wetlands, so any increase in crops (due to increased canola price) comes at the expense of wetlands. The results are again spatially heterogeneous, with similar conclusions as in Chapter 4: wetlands losses will be the smallest in north-eastern regions of the PPR.

Overall, the research indicates that climate change effects on wetlands are likely to be in the range of 34-56 percent from historic values, if a drier and warmer climate prevails. Linear regression models (Chapter 3 and 5) result in larger climate effects on wetland than nonlinear regression models (Chapter 4). Further, the estimate of land use change in Chapter 4 is higher than in Chapter 5 because we assume there are only two types of land in Chapter 4, and all gains in crops come at the expense of wetlands. However, the decrease in pasture land in Chapter 5 due to biofuel policies will also negatively impact waterfowl habitat. Thus, it is fair to assume that there will be some increase in cropped land at the expense of wetlands (and other waterfowl habitat) due to biofuel policies, particularly when there are more wetlands (i.e. when the marginal willingness to pay is lower). The results are sensitive to modeling assumptions and specification, however it is clear that wetlands and waterfowl habitat will significantly be reduced due to climate change, and both direct climate effects and land use change will play a role.

### **Policy considerations**

There are several policy implications based on the conclusions of this research. This line of research has implications for agri-environmental policies as well as climate change mitigation policies, as discussed in the conclusions of Chapters 3 and 4. However,

in this section, we focus on two main conclusion of this research, and discuss how policy could be implemented to address the issue. First, by including the social benefits of wetlands in the current bioeconomic model, this research concludes that wetlands are now and have been below socially optimal levels. Since it is in farmer's interest to drain wetlands while it is in society's interest to retain wetlands, government intervention is required to fix this market failure and manage wetlands in the PPR. The Canadian Government has identified wetlands loss as a major issue and has focused policy efforts on retaining wetlands. In this section we outline some policy tools that can be used to protect wetlands, discuss the policies that have and continue to be used in Canada, and discuss some of the best options for wetlands protection, based on the results of this work. Second, there is evidence that in a drier climate, wetlands loss will be significant, with the most pronounced effects in Saskatchewan and southern Alberta. Thus, the conservation efforts discussed below will be crucial in the future, and should focus primarily on Saskatchewan and Manitoba.

There are various policy tools available to government to manage wetlands at the socially optimal level. The main policy tools include extension (education, communication), informed inaction, and negative or positive incentives via regulatory or financial instruments (Pannell 2008). Positive financial incentives can include land use payments or land retirement payments, while negative financial incentives include environmental taxes (Claassen et al., p.7). Regulation, on the other hand, forces agents (polluters, poachers, etc) to follow restrictions on the level or type of activity to be practiced (Weersink et al., 1998).

Canada joined the North American Waterfowl Management Plan in 1986, which

is an international treaty for the protection of wetlands and waterfowl. This plan is discussed in detail in the introduction. Here, we discuss additional government policies and tools in Canada that have relevance to wetlands. In Canada, wetlands are primarily protected by the Federal Policy on Wetlands Conservation, enacted in 1991. The main goals of this policy are no net losses of wetlands on public lands, rehabilitation of wetlands that are at a critical stage, and to sustain wetlands for the use of future generations (Lynch-Stewart et al., 1999). There are also provincial policies on wetlands in Saskatchewan, Manitoba and Alberta, and other federal statutes that include wetlands conservation as a goal, including the following acts: Migratory Birds Convention Act, Canada Wildlife Act, National Parks Act, Canada Oceans Act Fisheries Act and the Canadian Environmental Assessment Act. Further, since 1981, Canada has been a part of the Ramsar international treaty on wetlands which advocates “the conservation and wise use of all wetlands through local, regional and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world” (Ramsar Convention Secretariat, 2007, p.2).

Despite the emphasis placed on wetlands conservation, wetlands management remains an issue in Canada as there is no comprehensive plan that has been implemented. These policies focus only on the protection of wetlands on Federal lands, and there are no policies that protect wetlands on private lands (Lynch-Stewart 1999). As a result, government programs have focused on education, voluntary action by farmers, and leading by example on Federal lands. However, wetlands on private lands continue to be drained for agricultural production. The need for more direct intervention has been identified over the last decade and Government has placed more emphasis on providing

direct financial incentives to retain and restore wetlands. In particular, Ducks Unlimited Canada (DUC) partnered with The National Farm Stewardship Program (NFSP) administered by Agriculture and Agri-Foods Canada. This program involved a cost sharing approach, where farmers who wish to restore wetlands will have 50 percent of the cost covered by the NFSP. Further, if the wetland is considered valuable waterfowl habitat, DUC would pay the other 50 percent.<sup>35</sup> Similarly, the US Conservation Reserve Program encourages farmers to convert highly erodible cropland to wetlands or other vegetative cover, in order to improve water quality, increase wildlife habitat and reduce erosion. The program, run by the USDA, also provides cost sharing assistance in order to convert land to ‘resource conserving covers’.<sup>36</sup> Finally, there are also programs that can protect wetlands with little cost to the treasury. Among these is ‘cross compliance’, which would require farmers to protect wetlands as a condition of receiving agricultural subsidies.

In concluding this section, we discuss which of the above policies have the most potential to effectively retain wetlands in Canada and which policies should be advocated in the future. Pannell (2008) states that if private benefits of wetland retention are negative, but social net benefits are positive, then voluntary policy options are insufficient and financial or regulatory incentives are necessary. Cortus et al. (2010) estimate that there are private costs of wetlands retention, however social benefits may

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<sup>35</sup> Details obtained at <http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1181580519716&lang=eng>, on December 2, 2011.

<sup>36</sup> Details obtained at <http://www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=crp> on June 12, 2012.

exceed private costs of wetlands retention. Further, the current research shows that by including social benefits of wetlands, the optimal value of wetlands to retain increases above historic levels. Therefore, it would appear that voluntary policy options are insufficient for managing wetlands in Canada.

Claassen et al. (2001) find that regulation is often avoided as it is inflexible, involves very high compliance and enforcement costs and can lead to inefficient allocations. Financial incentives, however, are flexible and efficient in achieving a social optimum. Whether positive or negative incentives are required depends on whether retention or restoration is the desired outcome and whether property rights are defined. As discussed in Cortus et al. (2010), if property rights for wetlands belong to landowners, then subsidies are required. If property rights belong to society and we wish to stop further draining, then taxation on drained land is required.

The discussion in this section suggests that financial incentives are required to optimally manage wetlands in Canada. While significant policy efforts have been made in Canada, none of it pertains to wetlands on private lands. Recent cost-sharing programs have been introduced, but there have not been enough incentives for farmers to stop draining wetlands on private lands. Given the benefits to society of retaining wetlands, subsidies and tax credits should be awarded to landowners who retain wetlands on their land. Payments need to be in line with estimates of net social benefits of wetlands and need to be significant enough to motivate change.

## **Future Research**

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

Wong et al. (2012) employ such spatial modeling, using an econometric panel-data model to examine the direct and indirect impacts of wetlands loss on waterfowl populations. The direct impact of wetlands loss is given by the reduction in waterfowl population in the stratum where the wetlands are lost, while the indirect effect relates to the change in populations in other, nearby strata. It turns out that the productivity of wetlands in other strata increases slightly, indicating that there is some accommodation of birds that have lost their primary reproductive habitat and been forced to seek habitat elsewhere. However, the extent of this mitigating effect is small.

The work of the current research could be extended to spatial and spatial-dynamic analysis, given the detailed wetland, crop and climate data by region and over time. A land used model could be developed using panel-regression and spatial econometric

methods (Anselin and Bera 1998) to determine the effect of climate change on wetlands, and whether climate change in nearby regions impacts the effect of climate change in a particular strata. Further, bioeconomic modeling of spatial-dynamic processes could help determine the movement and interaction of ducks across different regions of the PPR and the management of wetlands and waterfowl in a changing climate (Bateman et al. 2006; Weintrub et al. 2007; Sanchirico & Wilen 2006, 2008; Wilen 2007; Smith et al. 2009).

Finally, another limitation of this research is that the models in this dissertation do not explicitly address uncertainty. In some cases, we relied on sensitivity analysis to address randomness, however this may not lead to quite the same outcome as one in which explicit account is taken of uncertainty in making decisions. Johnson et al. (1997) developed a bioeconomic model of duck hunting in the Prairie Pothole Region, using a stochastic dynamic programming framework to address uncertainty related to random environmental and population variations and incomplete control over hunters' decisions. The models in Chapters 2-4 are also subject to these types of uncertainty, as well as uncertainty related to future climate change and agricultural prices. Future research needs to take such uncertainty into account. Models such as those in Chapters 2-4 could be solved as stochastic dynamic programming problems using mathematical programming software, in order to provide optimal paths (management strategies) given uncertainty.

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