Climate Change Impacts on agriculture/forestry land use patterns: Developing and applying an integrated economy-ecosystem response and adaptation impacts assessment model.

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I Introduction

Climate change will affect the ability of land resources to support different types of vegetation and thus alter production possibilities for agricultural and forestry producers. There is a need, therefore, to predict the potential consequences of anticipated environmental change on the stream of renewable goods and services derived from natural and managed ecosystems (including agricultural crops, timber and non-timber benefits) in Canada. These changes will undoubtedly change land values for given land uses. Changes in relative land values among competing land uses generally leads to changes in land management. It is also to be expected therefore, that landowners will adapt to climate by changing land-use and/or current management practices. Hence, the future effects of climate change will be a function of both the ecological responses to climate change and human adaptation. Not accounting for human adaptive responses may lead to incorrect estimates of the impacts of climate change on ecosystems, while ignoring ecological effects on land productivity will result in misleading forecasts of the socio-economic impacts. Developing credible estimates of the consequences of climate change requires a comprehensive modelling approach that integrates both economic and ecological systems.

In this project report, recent efforts to develop such a comprehensive modelling approach are described. The overall modelling effort in this project was divided into three components: a regional agricultural land values model, modification of the Integrated Biosphere Simulator or IBIS (Foley et al. 1996, 1997) to incorporate tracking of biomass by forest age class, and an integrated economy-ecosystem response and adaptation impacts assessment model. The IBIS model is an large-scale dynamic vegetation models that models vegetation responses to climate changes. The output from this model is an essential input into the economy-ecosystem model. The integrated economy-ecosystem model is a combined forest sector and agricultural sector model that uses inputs from IBIS and the agriculture land values models. One of the objectives of this model is to project agriculture and forest land use change by using estimating land values for the two sectors to determine optimal land use. The land values for the agriculture sector are projected using the agriculture land values model. The forestry land values are estimated and projected using a forest sector model that combines a timber demand model with a simple model of forest dynamics. The forest dynamics model receives input from IBIS to reflect changes in forest productivity in response to climate. Forest land values then reflect both market demands for wood and forest productivity as modified by changes in climate. The integrated economy-ecosystem model captures the essence of the land use possibilities in agriculture and forestry in response to climate change.

The report is divided into three sections that describe each of the three models. Of the three models the agriculture land values model is the most developed, and hence much of the report is devoted to it. The agricultural land values model is national in scope and allows for farmer adaptation to climate change. This report contains and assessment of climate change impacts on the agriculture sector using this model. This is followed by a description of changes that were made to the IBIS model so that it could provide input to the integrated economy-ecosystem model. The final section outlines the integrated economy-ecosystem model and describes some of the efforts to calibrate it to the province of Saskatchewan. Besides describing how the integrated model is calibrated this section also contains further results from the agriculture land values model and from the IBIS model.

2 A Regional Analysis of Climate Change Impacts on Canadian Agriculture

In the area of agriculture responses to climate change, recent studies suggest that the impacts on agricultural production, both for the USA and globally, will be negligible or positive (Lewandrowski and Schimmelpfennig 1999). These studies generally predict positive benefits for Canada which traditionally has been constrained by short growing seasons and unfavorable moisture regimes. Though net benefits for Canada may be positive it is expected that the distribution of costs and benefits across regions will be uneven. Regional studies on the potential impacts of climate change in Canadian agriculture have concentrated geographically on the Prairies and Ontario, limiting the scope for interregional comparisons. In addition, most research has focussed on the responses of specific crops such as grains and oilseeds and used crop response models as the main tool of analysis (Brklacich et al. 1999). One difficulty with crop response models is that they tend to overestimate the costs of climate change since the range of adaptation strategies available to producers is usually limited to a predetermined set of management variables.

Historical evidence suggests that the agricultural sector is very responsive to changes in economic opportunities, readily substituting inputs and adopting new technology in response to changes in prices and climatic conditions (Easterling 1996). Producers have a number of adaptation strategies available to them to reduce the costs or increase the benefits associated with climate change. These include switching land uses from pasture to crops or livestock, changing cultivars in the crop mix, and changing farm management variables such as seeding dates, planting densities, fertilization applications and irrigation practices. Previous studies that have incorporated adaptations have focused on changes in management techniques for given crop mixes or switching cultivars to enhance yields (*cf.* Brklacich and Stewart 1995; Brklacich et al. 1997). Studies that have allowed for the substitution of higher value crops and changes in land-use have limited adjustments to a select subset of crops with projected impacts derived from parameters in the literature or crop yield models (cf. Brklacich and Smit 1992; Mooney and Arthur 1990; Singh 1988; Smit 1987). These models are not capable of representing the full range of potential adaptive responses given the wide range of agro-climatic conditions that influence agricultural profitability in Canada. In addition, studies of observed farm level responses to climate have focused on responses to weather variability (risk) within particular climatic regimes rather than responses to changes in climate per se (e.g. Brklacich et al. 1997; Chiotti et al. 1997; Smit et al. 1996). To date there is no national scale econometric study of climate change impacts in agriculture that incorporates the full range of adaptation strategies undertaken by producers in response to climatic variation across regions.

2.1 The Regional Context

Agricultural productivity in Canada is constrained by both climate and soils. Only 10 percent of Canada's land supports economically viable agricultural production which takes place along an east-west band across the southern latitudes of the country (Environment Canada 1976). The most important climate variables that affect agricultural productivity are temperature, soil moisture, length of growing season, and severity of winter conditions (Bootsma 1999). For example, temperature affects the availability of heat units which has a significant impact on corn and soybean crop yields. The number of growing degree days (number of days above 5 degrees) affects the viability of long season crops such as spring wheat, potatoes and forages. Variations in autumn temperature result in differences in maturation dates, frost risk, and optimum times for seeding over-wintering crops such as winter wheat, clover, and alfalfa. Extreme cold and low snow cover also affect the survival of these crops. Horticultural crops and tree fruits in particular require mild winter temps and long warm growing seasons. The timing of precipitation is also a key factor in productivity. Excessive spring moisture can delay planting and increase the risk of disease while excessive fall moisture delays harvest, reducing the quality of crops and increasing frost risk. Precipitation variation also affects the number of days suitable for tillage and thus farm management decisions such as machinery size, labor requirements and irrigation.

Agroclimatic studies interpreting macro-climatic variations across the country in relation to agricultural potential provide a regional context for variations in agricultural productivity (c.f. Chapman and Brown 1966; Beattie, Bond and Manning 1981; Bootsma 1999; McCrae and Smith 2000). Canada's climate is moderated by the influences of the Pacific and Atlantic oceans, as well as the Great Lakes. These water bodies generate temperate influences in an otherwise harsh continental climate characterized by extreme temperatures and low precipitation. Only a small area of the country is currently suitable for growing fruits and cash crops such as corn, soybeans, and sugar beets, for which moderate winter temperature rather than the length of growing season is the critical growing factor.

On the West Coast mountains trap warm moist pacific air in winter and slow the movement of high-pressure systems in summer. The climate is characterized by low diurnal variation in summer temperature and infrequent occurrence of frost in winter. This creates a long temperate growing season attractive for horticultural crops such as fruits and vegetables that would otherwise be subject to winter kill. The most productive agricultural soils are found in the Fraser Valley and Southeastern Vancouver Island where horticulture and mixed farming predominate. The interior climate has greater temperature extremes in terms of both diurnal and seasonal variation. In the warmer drier montane cordillera, horticulture and livestock production dominate. The Peace River region of the Mackenzie Basin resembles the northern area of the Prairies and supports oilseed and grain production.

The absence of topographic features on the prairies allows cold air masses to move south from the arctic and warm air masses to move north from the U.S. unimpeded. The prairie climate is characterized by short hot summers and very cold winters. Annual precipitation is very low particularly during fall and winter months. The soils are fine textured with high fertility and good moisture holding capacity, making crops amenable to irrigation, particularly in the south which suffers from regular drought. Productivity is limited in the north by the boreal shield and short growing seasons. Plants grow more rapidly in the north due to longer days so that moisture rather than degree-days tends to be the limiting factor determining productivity on the Prairies. In fact high temperatures may have a detrimental impact on prairie productivity since they exacerbate moisture problems and hasten maturity thus reducing quality. Winter kill of forage crops, fruit trees and horticultural plants is a constraint on crop choice resulting in less agricultural diversity. The major commodities are grains and oil seeds although there has been a recent expansion in red meat, particularly in areas with low precipitation.

Southern Ontario and the St. Lawrence valley lie on a major storm track resulting in high precipitation distributed uniformly throughout the year (Chapman and Brown 1966). The temperate influence of the Great Lakes reduces the frequency of late spring and early fall frosts. This gives the region a comparative advantage in the production of fruit and vegetable crops. As a result, Ontario's agricultural sector is the most diversified in the country. Most of Ontario and Quebec's agriculture occurs in the mixedwood plains ecozone which contains Canada's most productive land. Agriculture extends into the southern boreal shield and Atlantic maritime ecozones, however the colder climate and less productive soils restrict agricultural activity to livestock and forage. The Atlantic provinces experience more storms than any other region in the country. The winters are cold, springs late, and the summers cool and cloudy. Moisture is excessive in spring and fall leading to short cool growing seasons. In addition, the soils tend to be acidic with poor texture. Agriculture in the Atlantic region is mixed with a concentration on livestock operations. Potato, cereal, and hay are the dominant crops.

The effects of climate variation on regional agricultural productivity are illustrated in Table 1 which provides a provincial breakdown of agricultural production for the year 1997. The Prairies dominate agricultural production both in terms of the percentage of land in agriculture and the share of Canadian agricultural GDP. The Atlantic provinces have the least amount of land in agriculture although on a per hectare basis Atlantic farms generate more receipts than farms in the Prairies. Ontario and Quebec generate the highest GDP relative to area in agriculture. Variations in land values reflect the value and intensity of agricultural land uses in different regions. High agricultural land values in Ontario and Quebec are associated with high value crops, while high land values in the Maritimes reflect the dominance of intensive land use in livestock operations. Productivity per hectare is lowest in the Prairies where land is cheap and farms are large scale operations efficient for grain and oilseed production.

Table 1. Regional Agricultural Productivity

Regional Agricultural Productivity					
Province	**Key Commodity Group**	**% of Agricultural GDP**	**Cash Receipts $M**	**% of Canadian Agricultural Land**	**Precent of Canadian Agricultural GDP**
British Columbia			**1,700**	**35%**	**7%**
	Grains and Oilseeds	1.5	25.5		
	Fruits and Vegetables	18.5	314.5		
	Dairy	19.5	331.5		
	Poultry and Eggs	19	323		
	Red Meats	16.5	280.5		
	Other	25	425		
Prairies			**14,500**	**81%**	**46%**
	Grains and Oilseeds	52	7540		
	Fruits and Vegetables	0.5	72.5		
	Dairy	4	580		
	Poultry and Eggs	2.5	362.5		
	Red Meats	33.5	4857.5		
	Other	7.5	1087.5		
Ontario			**6,600**	**8.30%**	**25%**
	Grains and Oilseeds	19	1254		
	Fruits and Vegetables	10	660		
	Dairy	18.5	1221		
	Poultry and Eggs	12	792		
	Red Meats	23	1518		
	Other	17.5	1155		
Quebec			**4,500**	**5.10%**	**17%**
	Grains and Oilseeds	8.5	382.5		
	Fruits and Vegetables	7	315		
	Dairy	30.5	1372.5		
	Poultry and Eggs	12.5	562.5		
	Red Meats	31	1395		
	Other	10.5	472.5		
Atlantic Provinces			**999**	**1.60%**	**4%**
	Grains and Oilseeds	1	9.99		
	Fruits and Vegetables	8	79.92		
	Dairy	22	219.78		
	Poultry and Eggs	17.5	174.825		
	Red Meats	18.5	184.815		
	Other	33	329.67		

Source: adapted from McRae and Smith, 2000.

2.3 Potential Impacts of Climate Change on Agricultural Productivity

A general overview of climate change scenarios based on global climate models (GCMs) suggests that over the next 20 years Canada can expect mean increases in temperature ranging from 1.39-2.68 degrees C. and mean increases in precipitation from 2.61-7.67% relative to 1961-1990 climate normals. Temperature and precipitation continue to increase so that by 2080 mean temperature increases range from 3.64-7.47 degrees C. and precipitation increases range from 9.13-17.83% (Canadian Institute for Climate Studies 2001). Temperature increases are expected to be more extreme in the northern latitudes due to the melting of the polar ice cap which allows heat from the ocean to escape into the atmosphere. While precipitation increases globally, most of the increase occurs over the ocean and coastal areas. On the other hand, significant areas of precipitation decrease are expected in the mid-continent (Canadian Institute for Climate Studies 2001). Decreases in precipitation coupled with increased temperatures will exacerbate moisture problems in interior areas already facing soil moisture constraints. It should be noted that precipitation is notoriously variable both spatially and temporally. Therefore regional results from individual GCM simulations can also be expected to vary significantly (Price 2001).

The net impacts of climate change are regionally specific. The reduction of frost risk and decrease in crop maturation time benefits the north more than the south where shorter maturation times actually reduce crop yields (Brklacich et al. 1999). Studies for Ontario and Quebec find that crop yields may either increase or decrease in response to changes in optimal growing conditions (Singh et al 1998). In the clay belts of northern Ontario and Quebec climate constraints on grain production are relaxed and new opportunities, particularly for corn, are expected (Brklacich et al. 1999). Grain yields are expected to decrease in grain producing areas, however these are offset by yield increases for higher value crops such as corn, soybeans, and fruit. Increased risk due to increased frequency of drought may offset these gains (Singh et al. 1991; Smit and Brklacich 1992; Smit 1987, Smit et al. 1989).

It is generally believed that climate change will have a positive impact on wheat yields in the prairies (Brklacich and Stewart 1995; Brklacich et al. 1999). Warmer frost-free seasons accelerate the development of grain crops and reduce time between seeding and harvest. Increased yields are also expected due to the fertilization effects of elevated levels of CO2. Increases in crop moisture stress and accelerated crop maturation rates may offset these effects in some regions, particularly in the Western Prairies. In the Eastern Prairies elevated CO2 levels and increases in precipitation are expected to increase cereal yields overall (Brklacich et al. 1999). Mooney and Arthur (1990) find that where yields for wheat, barley, and canola decrease, the substitution of higher value crops such as corn, sunflowers and soybeans offsets these reductions. In addition traditional crops are expected to migrate into marginal areas so that overall the costs of climate change on the Prairies will be low. However in the Southern Prairies (particularly Alberta and Saskatchewan), soil moisture deficits are expected to limit opportunities for crop substitution and hasten the decline in already marginal areas such as Palliser's triangle (Delcourt and Van Kooten 1995; Arthur and Van Kooten 1992).

2.4 Methodological Approach

Previous research has not incorporated the full range of adaptation strategies available to agricultural producers, nor have changes in production been linked to economic indicators such as land values. In addition, the use of differing methodologies has prohibited interregional comparisons at a national scale. Methodological approaches to estimating climate change impacts on agriculture can be divided into two categories. The "crop response" or production function approach is based on yield models that determine how specific crops respond to changes in environmental and management factors. The benefit of this approach is that it provides a detailed understanding of how physical, biological and management responses interact to determine changes in agricultural productivity at the farm level (Lewnadrowski and Schimmelpfennig 1999). Since the response functions are often derived from agronomic experiments, crop response models are capable of capturing responses to hypothetical states of the world, such as responses to increased levels of carbon fertilization, which can't be observed. Crop response models can also incorporate adaptive feedbacks between the market and individual decisions. However the range of adaptation considered depends on what is captured by the structural equations of the models (e.g. Adams et al. 1999). One drawback of crop simulation models is that they are data intensive and require relatively homogeneous regions in order for the results to be considered "representative" (Lewandrowski and Schimmelpfennig 1999). Thus they are not useful for large-scale inter-regional comparisons.

The "Ricardian" methodology is based on spatial analogues and uses cross section data on production, land values, and climate to infer how given climate change scenarios will shift the geographic production frontier (e.g. Mendelsohn, et al. 1994, 1996,1999; Segerson and Dixon 1999). The approach assumes that farm management decisions are optimal and reflect the long run equilibrium effects of climate and other geophysical and economic variables that are capitalized in land values. Spatial variation in land values is attributed to geoclimatic comparative advantage that can not be replicated. The Ricardian approach is well suited to capturing the tremendous range of agricultural heterogeneity across the country. Since these models are based on variations in observed production decisions across different climate regimes they incorporate the full extent of past adaptations to climate and are suitable for macro level analysis. Cross-section estimates of land values are the basis for projections of climate change impacts. By examining changes in agricultural land values we can infer the benefits of climate change to agricultural productivity.

While our view is that the Ricardian approach is a useful way to proceed, the reader should be aware of the drawbacks to this approach. First, it requires data to be representative of actual factors influencing farm level decisions, and relies on statistical analysis to isolate confounding effects (Lewandrowski and Schimmelpfennig 1999). In addition the cross-section approach is limited to adaptations based on climate variation in the observed data, and may not accurately predict the effects of climate conditions outside the range of variation in the data, or factors such as changes in CO2 concentration levels. This is a potentially important caveat for Canadian analysis since the variation in climate across agriculturally productive regions is not as large as in other countries such as the United States where this methodology has been previously applied.

2.5 Estimation

Data on agricultural land values were obtained from the 1996 Agricultural Census (Statistics Canada 1996a). The reported market values of land and farm buildings are assumed to reflect the discounted present value of returns to agriculture.[1] Demographic information related to non-agricultural influences on land values such as average housing values and population density were obtained from the 1996 Census of Canada (Statistics

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[1] While reported land values may be distorted there is no reason to believe that they are systematically biased. Therefore these values are taken to be a fair proxy of actual market values of agricultural land.

Canada 1996b). Soils data were obtained from the Canadian National Soil Database (Centre for Land and Biological Resources Research 1996). Baseline climate data were made available by Natural Resources Canada and are based on monthly climate normals for temperature and precipitation from 1961-1990 provided by weather stations by Environment Canada. Weather station data were interpolated to generate historical normals for mean monthly temperature and precipitation at $10km^2$ resolution for the entire country (Price et al. 2000; Price et al. 2001). Census and soils data were intersected with the climate data in a GIS database to define a new gridded data set at $20km^2$ resolution.

Figure 1 shows the distribution of per hectare agricultural land values across Canada for 1996. The average value was $2285 with minimum and maximum values of $273 (Newfoundland) and $33,273 (British Columbia) respectively. There is significant spatial clustering of land values due to geoclimatic factors as well as other influences such as proximity to large populations and water bodies. Since both population and access to markets are concentrated in the south there is also a positive southward trend in land values. We removed several observations for which agricultural land values were deemed to be outliers based on the studentized residual test (Belsey, Kuh, and Welsch 1980). These observations were concentrated near Vancouver and on Vancouver Island, as well as in Southern Ontario near Toronto and Lake Ontario. We believe reported market values for land in these locations were elevated by factors unrelated to agricultural productivity such as proximity to densely populated metropolitan centers and restrictions on transferring land from agricultural to non-agricultural uses. The final data set consists of 3665 observations. Each observation was weighted by the percentage of land in agricultural production. Areas with a large percentage of land in agriculture are assumed to provide a better reading on agricultural practices. We also expect variances in average land values to be negatively correlated with the percentage of land in agriculture.

Climate variables were derived from monthly averages for the midpoint months of the four seasons (DJF, MAM, JJA, and SON). January and July variables reflect the effects of annual climate extremes, while April and October variables reflect the effects of length of growing season and seasonal variations in moisture. Climate variables are assumed to have non-linear impacts on agricultural productivity. In particular it is thought that there is some optimum level of heat and moisture for producing crops (Grigg 1995). These effects were approximated by piece-wise linear terms based on median values of the climate data. The first linear term for each season reflects the marginal value of the climate variable (temperature or precipitation for each season) while the second linear term reflects the increase or decrease in the marginal value of the variable above the median. All climate variables are expressed as deviations from the mean in order to reduce the amount of collinearity in the data.

Interaction terms were constructed to capture the combined effects of low precipitation and heat on soil moisture. Interaction terms were derived by multiplying a dummy variable indicating whether or not an observation fell within the lowest quartile of total annual precipitation with the temperature variables. Areas of low precipitation are illustrated in Figure 2. As with the temperature and precipitation variables, the median terms are meant to capture non-linearities in the relationship between soil moisture and temperature. A complete definition of variables used in the study is given in Appendix A.

The results of the empirical analysis are reported in Table 2. Regressions1-3 show the impacts of climate on agricultural land values with and without interaction terms. Variables with 95% significance are indicated in bold. The coefficients on temperature and precipitation represent the amount by which the value of land will increase due to a one-degree increase in temperature (respectively a one-millimeter increase in rainfall). The effects of the median variables are additive. For example, according to OLS1, a one-millimeter increase in July rainfall will increase land values by $48.27 per hectare. If precipitation is greater than the median level of precipitation for the country, then a one millimeter increase in rainfall will increase the value of land by $15.24 per hectare, which is equal to the sum of the "July Rain" coefficient (48.27) and the "July Rain Median" coefficient (-33.03).

The effects of climate and non-climate variables are similar for all three models. For ease of exposition we will confine our discussion to OLS2 which includes interaction terms for low precipitation effects. Direct interpretation of the regression coefficients in relation to specific impacts on yields and cropping decisions is not possible within this framework. However we can speculate to some extent about what might be driving the results, particularly with respect to the direction of the signs on the coefficients. For example, the effect of precipitation is positive in all seasons except the fall. The negative coefficient on October rainfall likely reflects the decrease in crop quality and increase in frost risk associated with wet weather during harvest season. January and April precipitation have positive and increasing effects above the median. This is probably due to the importance of spring moisture for crops which is a limiting factor on the prairies.

April and July temperature increases have an unambiguously positive effect on land values. The positive effect of April temperature is probably related to an increase in the length of the growing season which creates opportunities for switching from lower to higher value crops. The positive coefficient on July temperature may indicate that the decrease in the value of grain crops due to quicker maturation is outweighed by the ability to switch to higher value corn and soybean crops that require higher heat units. The coefficient on January temperature is negative below the median and positive above the median. Observations with January temperatures below the median are located in the Prairies and warmer temperatures in this range of this distribution occur where there is less rainfall. Thus the negative coefficient may reflect interactions between temperature and precipitation not included in the regression. Above the median the net effect of an increase in January temperature is positive, perhaps reflecting a threshold winter temperature for higher value horticultural and over wintering crops. As expected the coefficients on the interaction terms are negative for January, April, and July, reflecting the effects of soil moisture constraints on agricultural productivity. Interestingly the interaction effect is positive for October probably reflecting the fact that low precipitation and warm fall temperatures are associated with higher quality crops due to reduced frost risk (e.g. Bootsma 1999).

Average dwelling values are used as a proxy for demographic and urbanization trends that affect regional land values. As expected the coefficient is positive. Provincial dummy variables are included to reflect the effects of the provincial agricultural policy regime and are measured relative to Manitoba. Provincial variables are positive for British Columbia and Alberta, and negative everywhere else. Dummy variables were also included for soil type. Chernozyms are fertile agricultural soils found throughout the Prairies. The effects of the soil variables are measured relative to chernozyms. Soils that commonly occur under forests such as brunisols, and podzols have negative effects on land values because they are poor quality for agriculture and constrain growth and farm management choices in areas where they are dominant. Luvisols and gleysols that occur more frequently in agricultural landscapes have positive coefficients. Although regosols are new undeveloped soils not suitable for agricultural crops, they occur along fresh water networks. The positive coefficient on regosols reflects their proximity to water in the Southern Prairies. Finally solonetzic soils which are associated with saline parent materials have a negative effect on land values. Soil chemistry variables were initially included in the regression, but were insignificant. We omitted agricultural management variables such as farm size and irrigation from the regression as the choice of management regime is endogenous.

2.6 Impacts of Global Warming for Agricultural Land Values.

The results from OLS2 were used to project the effects of global warming on agricultural land values. The climate change scenario is based on the CGCMII model developed by the Canadian Centre for Climate Modeling and Analysis (CCCma). The climate scenario represents the output for a single model run based on one projection of GHG and aerosol emissions over the period 1950-2070. Output from the simulation were downscaled to 10km resolution in order to provide spatially detailed projections of changes in Canada's climate suitable for regional impact analysis (Price et al. 2001). The projections reflect moving averages calculated from 30 simulated years that are directly comparable to 1961-1990 normals. The greatest increases in temperature occur in the northern and central regions of the country. Winter minima increase the most, particularly in the Southern Prairies where average changes exceed 6 degrees during the period 2041-70.

Table 2: Regression Results

Variable	OLS1	OLS2	OLS3
January Rain	**625.68**	2.82	3.65
	1.68	0.73	0.95
January Rain Median	**9.43**	**13.82**	**12.99**
	2.94	4.17	3.91
April Rain	**28.78**	**24.60**	**24.70**
	6.75	5.72	5.65
April Rain Median	**22.31**	**24.06**	**24.31**
	5.81	6.10	5.92
July Rain	**48.27**	**41.99**	**45.53**
	14.93	11.43	11.39
July Rain Median	**-33.03**	**-32.39**	**-37.04**
	-6.60	-6.08	-6.57
October Rain	-1.67	-1.76	-3.10
	-0.39	-0.41	-0.71
October Rain Median	**-5.30**	-4.35	-3.87
	-1.47	-1.21	-1.07
January Temperature	**-96.47**	**-44.20**	**-56.62**
	-4.78	-1.85	-2.33
January Temperature Median	**402.32**	**385.05**	**436.60**
	14.42	13.27	12.62
April Temperature	**208.19**	**217.69**	**210.11**
	3.35	3.33	3.10
April Temperature Median	**449.53**	**611.90**	**656.11**
	6.25	7.84	7.73
July Temperature	47.63	101.01	87.56
	0.82	1.59	1.32
July Temperature Median	10.96	48.97	77.43
	0.24	0.99	1.42
October Temperature	118.52	-35.39	18.39
	1.60	-0.43	0.21
October Temperature Median	**-230.83**	**-322.96**	**-488.53**
	-2.98	-4.08	-5.01

January Interaction		**-86.96** -3.17	**-49.96** -1.64
April Interaction		**-375.89** -5.00	-36.20 -0.16
July Interaction		**-174.38** -2.31	-191.03 -1.45
October Interaction		**488.95** 4.48	125.15 0.75
January Interaction Median			**-122.76** -2.58
April Interaction Median			**-394.39** -1.67
July Interaction Median			34.93 0.32
October Interaction Median			**588.05** 3.32
Housing Value	**0.0046** 10.07	**0.0045** 9.80	**0.0045** 9.82
Rooting Depth	**221.18** 5.43	**176.89** 4.28	**165.22** 3.90
Water Capacity	**55.38** 3.48	**63.19** 3.91	**65.46** 4.05
BC	**1971.90** 8.09	**1653.40** 6.68	**1632.80** 6.57
AB	**266.25** 2.17	**223.48** 1.74	**221.92** 1.72
SK	26.33 0.25	61.81 0.53	71.14 0.61
ON	**-365.35** -1.84	-204.45 -0.98	-65.96 -0.31
QUE	**-364.99** -1.86	-124.28 -0.59	18.19 0.08
NB	**-2181.40** -7.64	**-1766.30** -5.91	**-1590.90** -5.24

NS	**-4140.30** -12.74	**-3626.80** -10.74	**-3457.30** -10.09
PEI	137.68 0.32	663.86 1.48	**854.44** 1.89
NFD	**-2453.30** -4.32	**-2046.80** -3.59	**-2043.40** -3.58
Brunisol	**-334.53** -3.11	**-328.36** -3.06	**-313.51** -2.92
Gleysol	**196.52** 1.77	**195.66** 1.76	**217.10** 1.95
Luvisol	**115.61** 1.66	**147.71** 2.11	**151.95** 2.14
Podzol	**-428.64** -3.19	**-366.17** -2.73	**-359.20** -2.67
Regosol	13.43 0.15	21.63 0.25	21.63 0.25
Solonetzic	-48.21 -0.62	-18.30 -0.23	-11.47 -0.14
CONSTANT	-92.13 -0.28	-33.72 -0.10	-118.78 -0.37
Adjusted R2	**R2=.75**	**R2=.75**	**R2=.75**

Increases in spring, summer and fall temperatures are smaller. Generally precipitation increases over time, on average by 5% from 2000-2070. However there are significant regional decreases, particularly in the Southern Prairies and BC (Price et al. 2001). Overall the implication for the interaction terms used in our study is that the number of observations for which annual total precipitation falls below the 25th percentile of the 1961-90 norm decreases 16% by 2031.

Table 3 reports the predicted impact of climate change on agricultural land values by province for three 30-year average periods. The results are also mapped in Figure 3. Predicted climate driven increases in land values average \$1888 for the 30-year period 2031-61. Ontario, Alberta and Saskatchewan experience the greatest increases with average gains of over \$2000 per hectare. In percentage terms the benefits of climate

Table 3.

Average Rent per Hectare by Province for OLS 2

	PROVINCE										
	BC	**AB**	**SK**	**MN**	**ON**	**QUE**	**NB**	**NS**	**PEI**	**NFD**	**Total**
Actual 1961-90	**4095.72**	**1327.68**	**809.70**	**944.24**	**4405.46**	**2265.52**	**2072.10**	**2069.89**	**4099.39**	**3617.51**	**2284.78**
Predicted 1961-90											
# observations	869.00	822.00	775.00	318.00	359.00	244.00	114.00	111.00	7.00	46.00	3665.00
climate	2172.47	-126.15	-405.15	-53.09	3471.11	2226.93	3220.54	6189.91	2821.33	4773.06	1237.75
other	2314.43	1328.98	1235.79	1031.73	1079.55	592.64	-1215.72	-3358.55	1068.26	-1569.10	1185.69
Predicted Total	**4486.91**	**1202.83**	**830.64**	**978.64**	**4550.65**	**2819.57**	**2004.82**	**2831.36**	**3889.59**	**3203.95**	**2423.44**
Projected Change in Rent per Hectare											
2011-2041	980.28	1675.51	1711.72	1315.68	1676.01	998.76	990.84	414.67	581.92	-257.59	1356.26
2021-2051	1005.67	1818.14	1623.88	1546.27	2248.22	1133.26	1094.35	561.07	1163.80	-2.46	1472.68
2031-2061	1267.49	2155.58	2029.10	1748.89	2867.03	1877.75	1969.67	1403.65	1961.56	747.73	1887.57
Projected Total Rent per Hectare											
2011-2041	5467.18	2878.34	2542.36	2294.32	6226.67	3818.34	2995.66	3246.03	4471.51	2946.36	3779.70
2021-2051	5492.58	3020.97	2454.52	2524.91	6798.88	3952.83	3099.17	3392.43	5053.40	3201.49	3896.11
2031-2061	5754.39	3358.41	2859.74	2727.52	7417.68	4697.32	3974.49	4235.01	5851.16	3951.69	4311.01
Percentage Change in Rent per Hectare											
2011-2041	21.85%	139.30%	206.07%	134.44%	36.83%	35.42%	49.42%	14.65%	14.96%	-8.04%	55.96%
2021-2051	22.41%	151.16%	195.50%	158.00%	49.40%	40.19%	54.59%	19.82%	29.92%	-0.08%	60.77%
2031-2061	28.25%	179.21%	244.28%	178.71%	63.00%	66.60%	98.25%	49.58%	50.43%	23.34%	77.89%

change appear substantial. However it should be noted that percentage changes are relative to initial values, and a large portion of Canadian agriculture takes place along the margins of feasible cultivation. Percentage increases are highest in the Prairies where January and April temperatures are expected to increase significantly. This suggests that increases in the Prairies may be driven by increases in length of growing season and the production of more valuable winter crops due to milder winter conditions. Dry conditions temper but do not eliminate predicted increases in land values in the Southern Prairies. The Peace River region, which was marginal to begin with, experiences only moderate increases in temperature and precipitation. The model predicts that this region will experience a decline in land values over time. This may suggest that winter temperatures in this area do not reach a minimum threshold for switching to higher value crops.

Under the current climate the Prairies rank lowest in terms of returns to agricultural land, with average values per hectare less than 50% below the mean for Canada. This is partially a result of the intensity of land use for the types of agriculture practiced in these provinces. Low land values are also driven by climate variables, particularly in the Southern Prairies where soil moisture constraints are a factor. The model predicts that benefits of climate change to the Maritime provinces are low, particularly for

Newfoundland which experiences an initial decline in average land values due to increased levels of precipitation in every season (particularly July and October) along with relatively mild warming trends. Similarly the model predicts a decline in land values for the West Coast due to high levels of precipitation and small temperature increases. In spite of these trends, climate change does not alter the relative distribution of land values as the substantial gains predicted for the Prairies are not large enough to overcome the climatic advantages of other regions.

The results of our analysis may seem overly optimistic, particularly when high temperatures and drought conditions over the past few years have created enormous hardship for agricultural producers in the Prairies. Conventional wisdom asserts that greenhouse gas driven increases in soil moisture deficits will lead to a decline in the agricultural sector in the Southern Prairies while our model predicts substantial increases in land values for this area. Thus some discussion of our results in this context is warranted. First, it is necessary to emphasize that our climate change projections are derived from downscaled results from a single GCM run for a single emissions scenario. Given the spatial and temporal variability of precipitation it is more important to focus on the overall trend in impacts over time than on particular values for a particular year. Secondly, the interaction terms are rough proxies for potential moisture deficits in the current climate and are not derived from an underlying water balance model. Therefore they probably do not capture the full costs associated with increased temperatures and decreased precipitation. It does not necessarily follow, however, that future increases in evapotranspiration in the Prairies will lead to a decline in agricultural land values. This is because currently producers adapt to dry climates through irrigation.

The model predicts the substitution of higher value irrigated crops will outweigh the costs associated with low natural precipitation. In addition, dry areas in the Prairies correspond to areas where soils have high water holding capacity. This will help get irrigated crops through seasonal moisture deficits. Thus the fundamental assumption which needs to be addressed is not the degree to which increased evapotranspiration will lead to a decrease in soil moisture. Rather it is the extent to which irrigation will be feasible in regions that experience increases in soil moisture deficits. This will depend on the ability to augment supplies, particularly in the Southern Prairies where water resources are currently near or fully allocated. On the other hand, current water shortages should not be used as the basis for predicting future water constraints. Given that most water used for irrigation in Canada is not priced, there is no incentive in the current system to undertake conservation measures that might increase the availability of water in the future.

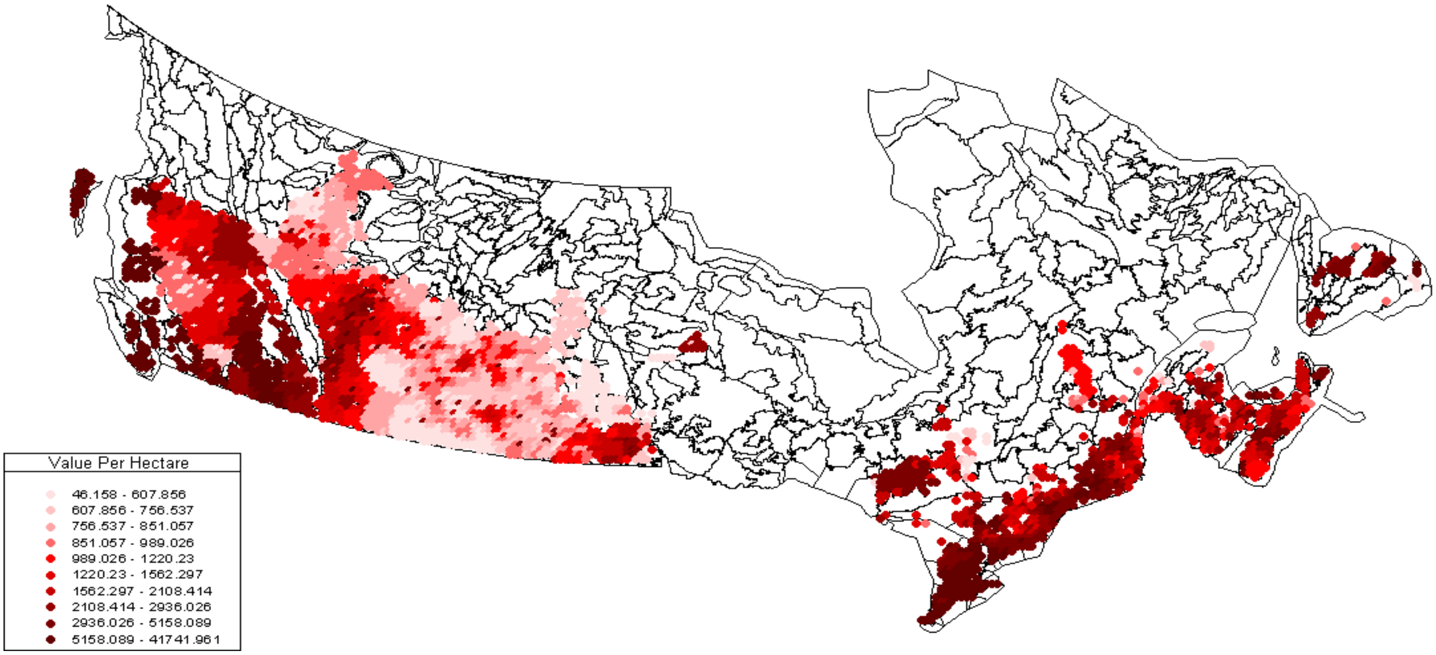
The Ricardian approach represents an upper bound on the potential benefits of climate change. Difficulties with the approach can arise when projecting for climate impacts outside of the natural range of variability in the data. In particular, the model may underestimate damages associated with a worsening of poor climate conditions and overestimate the benefits of climate change in areas with warmer climates. Another problem with the approach is the implicit assumption that marginal impacts from climate can be examined separately and that a continuous gradient of adaptation over the range of climate variables is feasible. It is likely that the linkages between the various components that contribute to agricultural productivity are more important than individual factors - that is, the influence of the sum is greater than the individual parts. For example, Adams, Alig, et al. (1999) find that while crops migrate easily within the same geoclimatic zone, soils barriers prevent migration of most crops and agriculture technology across large regions. This would cause the Ricardian approach to overstate the range of adaptations available to farmers at different locations. On the other hand, as returns to agriculture increase there will be pressure to expand the margin of cultivation further north. Darwin et al (1995) find net increases of cropland in Canada ranging from 49.1-112.3%. In addition, Canada's global position in the trade of wheat and grain corn is expected to improve as production prospects in the rest of the world decline (Smit 1989). These additional positive benefits are also not captured in the Ricardian framework.

2.7 Conclusions

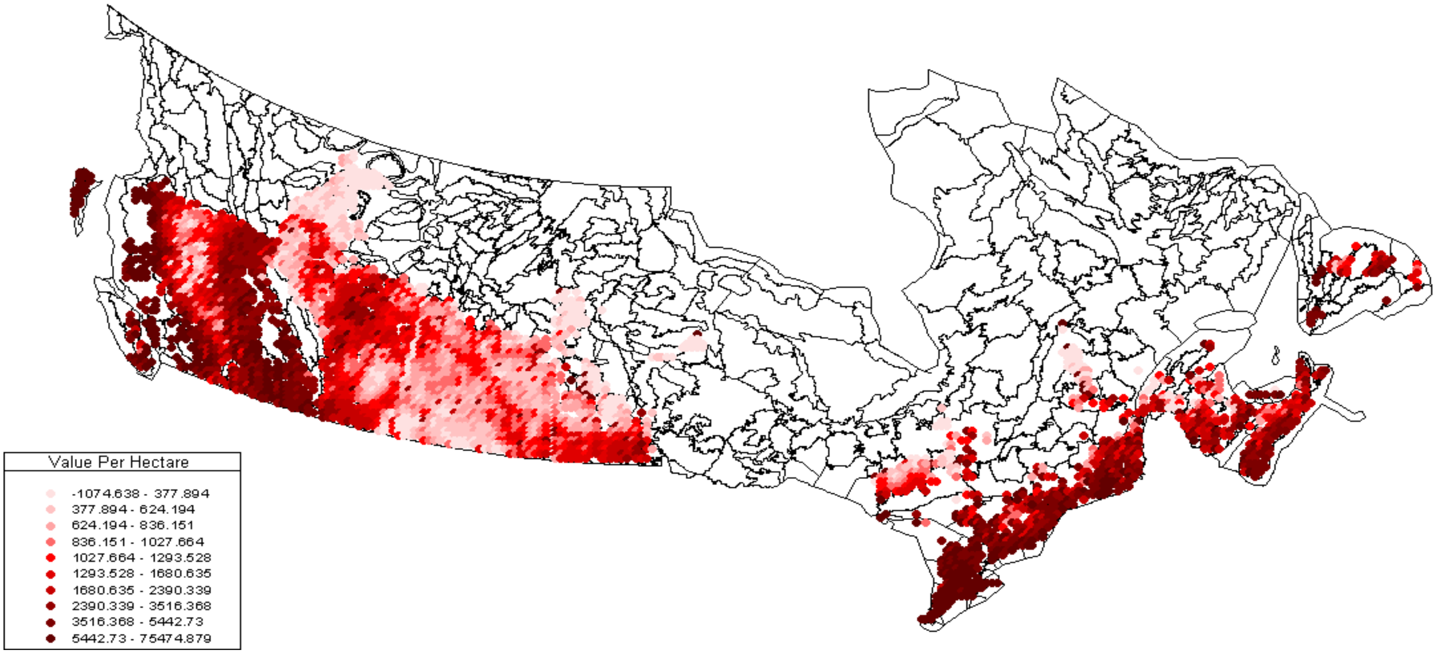
Previous research on the impact of climate change on Canadian agriculture has suggested that while climate warming will relax constraints on the growing season, the benefits of warmer temperatures may be offset in many regions by increases in evapotranspiration, soil moisture deficits, and rapid maturation of grain crops. Previous research has focussed on particular regions and differing methodologies have made inter-regional comparisons difficult. In addition, by focussing on yield impacts for particular crops, the full range of potential adaptations has not been included, overestimating the predicted costs associated with climate change. We address this gap in the literature by developing a cross-sectional econometric model of agricultural land values for Canada. Optimal adjustments to climate variations are assumed to be capitalized in agricultural land values that are used as proxies for estimating changes in productivity due to climate change. We find that while all regions benefit from climate change, the relative gain is greatest for the Prairies and lowest for coastal regions. In absolute terms Ontario experiences the largest gains. The regional ranking of agricultural land values doesn't change.

Our results suggest that previous studies have been overly pessimistic in estimating the costs of climate change. However the results should be interpreted as an upper bound on potential benefits rather than estimates of what will actually occur. In spite of the limitations of the approach we believe that our results illustrate the potential direction of change in agricultural land values. Future research that utilizes the Ricardian approach should aim at extending the method to identify physical constraints to adaptation, such as climate threshold effects, soil profiles, and soil moisture deficits that are not fully captured in the model presented here. Finally if any of these gains are to be realized, governments will have to dismantle policies that may inhibit the adjustment process. Such policies might include crop insurance programs which cover only select crops in particular regions based on current cropping patterns, or other agricultural support policies which target particular activities.

Figure 1: Quantile Distribution of Canadian Agricultural Land Values, 1996.

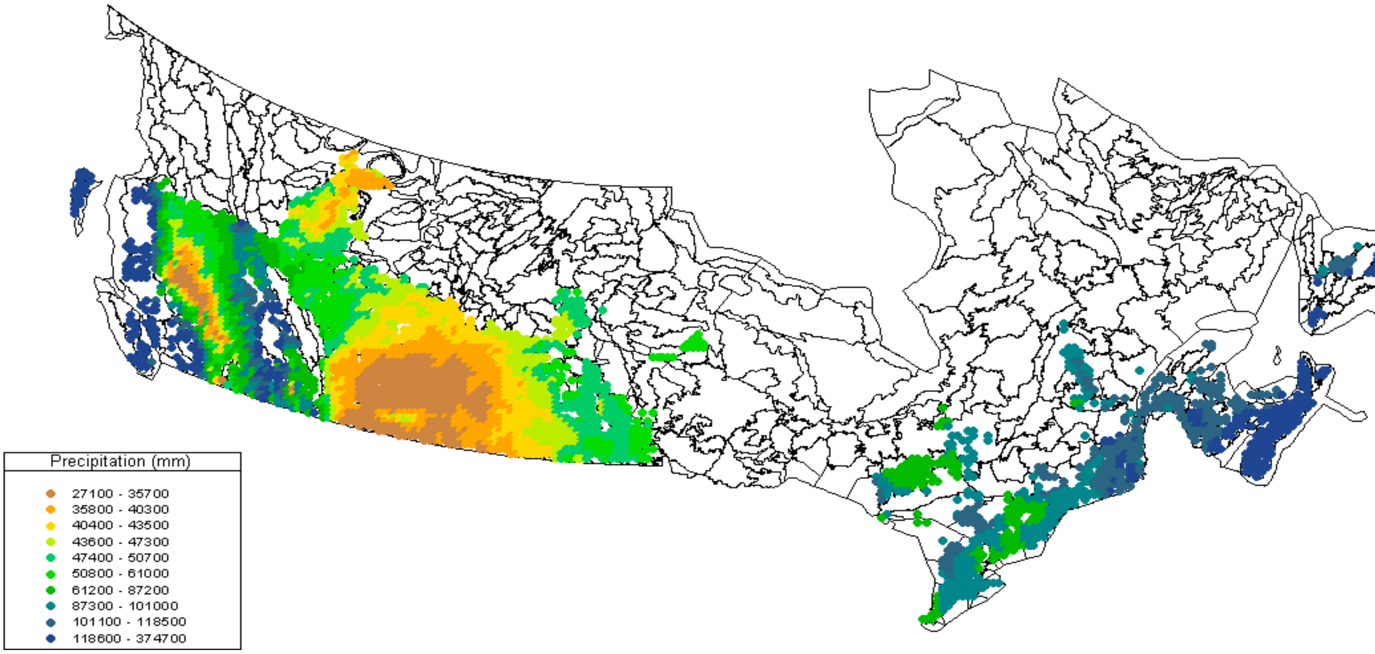


(a) Actual Rent Per Hectare 1961-1990

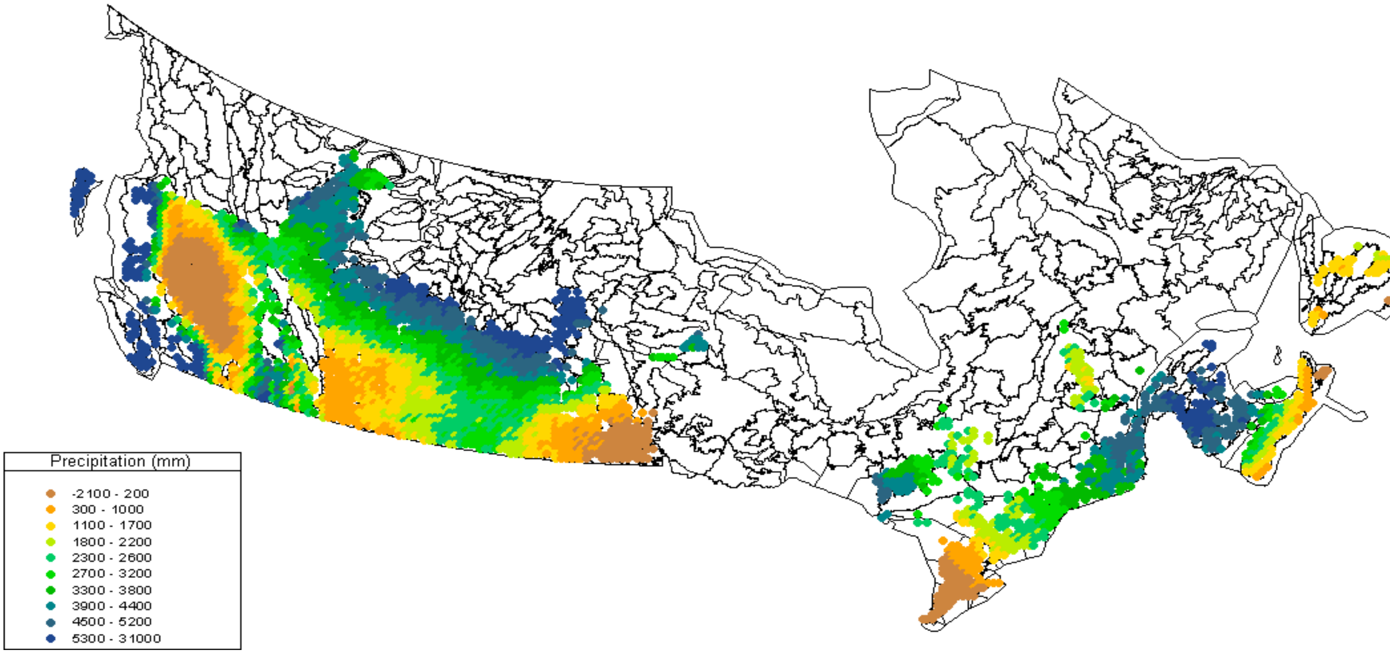


(b) Predicted Rent Per Hectare 1961-1990.

Figure 2: Total Annual Precipitation.

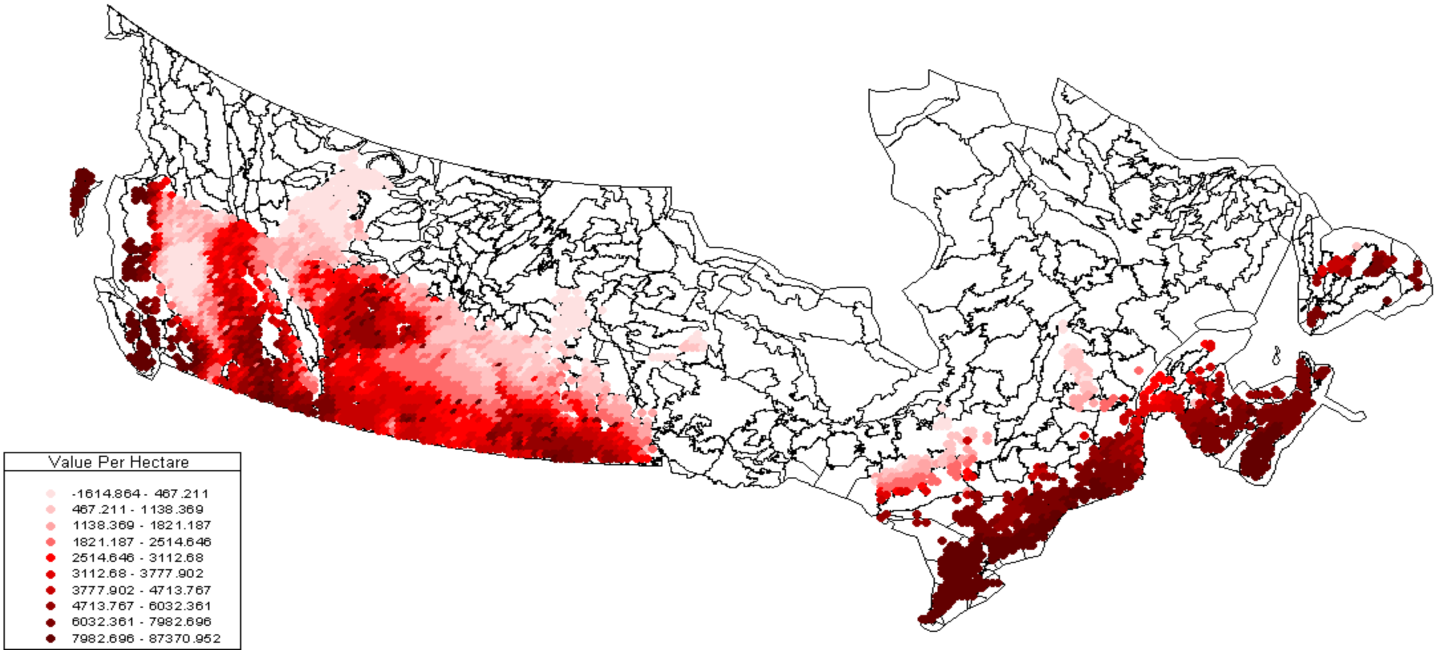


(a) Actual Annual Precipitation 1961-1990 Climate Normals

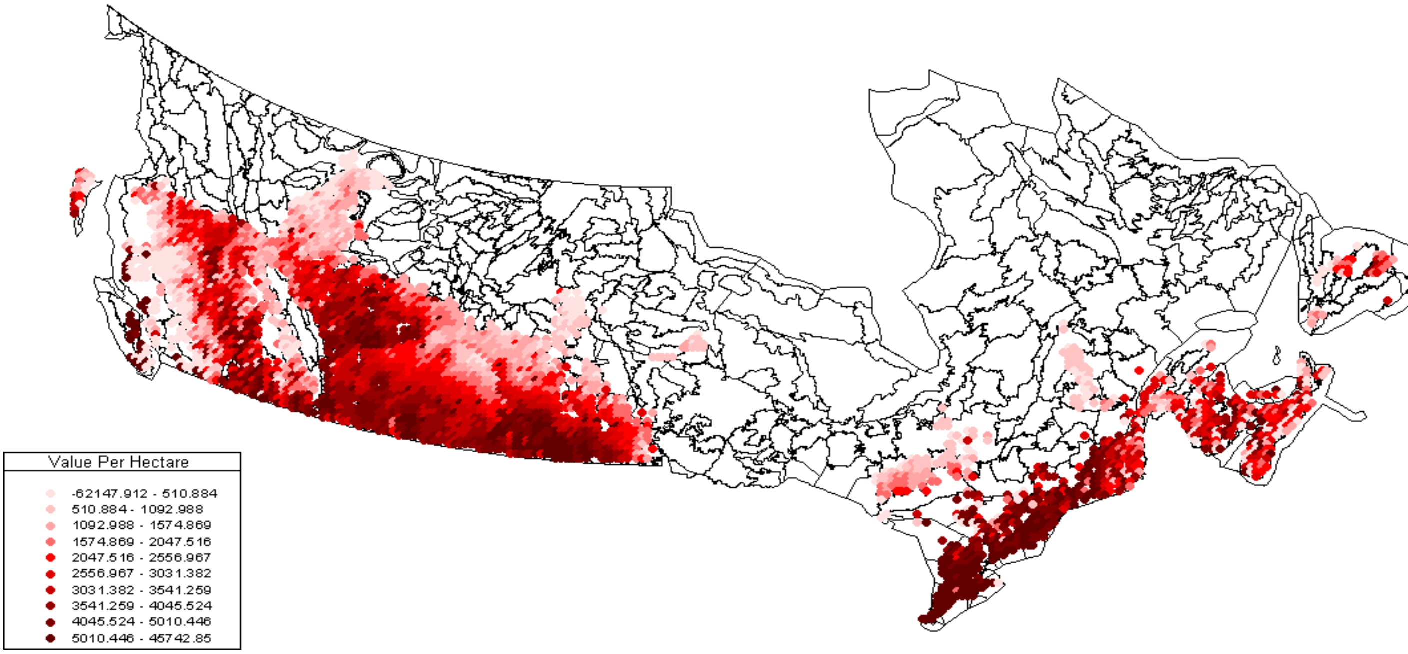


(b) Predicted Change in Annual Precipitation (1961-1990) – (2031-2060)

Figure 3: Impacts of Climate Change on Canadian Agricultural Land Values.



(a) Predicted Rent Per Hectare 2031-2060



(b) Change in Predicted Rent per Hectare (1961-1990) – (2031-2060)

2.8. Appendix to Section 2: Definitions of Variables Used in Regressions

January Rain
Mean January precipitation (mm) based on 1961-1990 climate normals.

January Rain Median
January precipitation (mm) if above median of mean January precipitation based on 1961-1990 climate normals.

January Temperature
Mean January temperature (degrees celcius) based on 1961-1990 climate normals.

January Temperature Median
Mean monthly average temperature (degrees celcius) if above median of mean January temperature based on 1961-1990 climate normals.

January Interaction
Mean January temperature if mean annual total precipitation is below the 25th percentile based on 1961-1990 climate normals.

January Interaction Median
January interaction term if January temperature variable is above the median of mean January temperature based on 1961-1990 climate normals.

Housing Value
Average dwelling value reported by 1996 census subdivision.

Rooting Depth
Unrestricted rooting depth class (cm) of the dominant soil landscape from the Soil Landscapes of Canada Version 2.2 (SLCV2.2) database.

Water Capacity
Available water capacity defined as the portion of water in a soil that can be readily absorbed by plant roots in the upper 120 cm. of the dominant soil landscape from SLCV2.2

BC, AB, SK, ON, QUE, NB, NS, PEI, NFD
Dummy variables for all provinces.

Brunisol, Gleysol, Luvisol, Podzol, Regosol, Solonetzic
Dummy variables based on the soil name associated with the dominant soil landscape from SLCV2.2.

3. Using IBIS and Dynamic Forest/Agriculture Sector Model for Integrated assessment of climate change effects on forest systems with non-linear response paths

In section 2 an agriculture land values model was developed. In section 4, an integrated economy-ecosystem model that links agriculture and forest sectors and incorporates climate change impacts on both sectors is developed. In this section, the IBIS model or Integrated Biosphere Simulator and modifications to this system that allow it to link with the integrated economy-ecosystem model are described. In this study the IBIS model is used primarily to project changes in forest ecosystems that are induced by climate change. These projected changes are then used as inputs into the economy-ecosystem model described in section 4.

Forests are closely linked to the social, cultural and economic infrastructure of communities in North America, Europe and northern Asia. There is a need, therefore, to predict the potential consequences of anticipated environmental change on the stream of renewable goods and services derived from natural and managed ecosystems (including agricultural crops, timber and non-timber benefits) in northern countries. Changes in land rents and/or property values generally lead to changes in land management. It is also to be expected therefore, that landowners will adapt to climate change by trading land, or by changing land-use and/or current management practices. Hence, the future effects of climate change will be a function of both the ecological responses to climate change and human adaptation. Not accounting for human adaptive responses may lead to incorrect estimates of the impacts of climate change on ecosystems, while ignoring ecological effects on land productivity will result in misleading forecasts of the socio-economic impacts. Developing credible estimates of the consequences of climate change requires a comprehensive modelling approach that integrates both economic and ecological systems.

Major ecological concerns include changes in the distribution and geographic range of productive forests, changes in species composition affecting non-timber values, and increased areas lost due to natural disturbances. Economic concerns include regional and national timber supplies, changes in economically appropriate land-use, land values, and accessibility for harvesting and tourism. Social consequences include the fate of rural communities that rely on local forests as economic drivers (via forest operations, saw- and pulp-milling, tourism, hunting). Both rates of change and the duration of periods of adjustment may be critical.

To date, a limitation of integrated assessment modelling efforts has been the assumption that ecosystems change linearly from their existing state toward some future stable condition. Realistic assessments of the ecological effects of environmental change, however, require process-based models that include physically and physiologically correct representations of climate-vegetation interactions over time. Given the timeframe during which these effects are expected to occur (next 50-100 years), these transient responses may be much more important than end-point equilibria. The recent development of large-scale dynamic vegetation models (DVMs) is seen as an important step in providing such information. Successful integration of the economic consequences of transient changes, however, requires more than a simple linkage of ecosystem model output to economic model input. It also needs well-defined representation of continuous feedbacks between the ecological and economic components, and also among different sectors of the economy (e.g., changes in land-use between agriculture and forestry).

A major complication results from the *interactions* between forest ecosystems as suppliers of goods and services, and the adaptive management strategies which can be imposed on them as conditions change. For example, Sohngen and Mendelsohn (1999) integrate models used to assess the impacts of a range of climate change scenarios on vegetation zones within the U.S. with a dynamic model of the U.S. timber market. Following their example, in this project we are creating a spatial, dynamic, integrated assessment model for predicting changes in rural land-use in Canada in response to plausible scenarios of climate change, mediated by natural ecosystem responses and adaptations in management. A dynamic linkage will be built between the IBIS DVM of Foley et al. (1996, 1997) and an economic model of property values for land (including marginal agricultural land and private forest land where possible). Using the DVM's annual estimates of changes in net primary productivity and biomass as indicators of forest production and future timber availability changes in product supply and demand, price equilibrium and land distribution can be modelled. Management feedbacks must then be related to economic impacts and forecasts of ecosystem responses (using the DVM's predictions as "decision support"), for different scenarios of change.

This paper will firstly describe how IBIS is being used to investigate climate change effects on Canada's forests and the outputs available for economic assessment. Particular emphasis will be placed on the need to represent age-class dynamics so that the effects of climate-related changes in natural disturbance regimes, and the effects of management on timber supply can be assessed. A formulation for an economic assessment model that uses IBIS output to adjust projections of land inventory data will then be described. Finally, current progress towards developing a fully-integrated assessment model will be described.

3.1 Problem Definition - Canada's Forested Ecosystems 1900-2100

Forestry is a major contributor to Canada's economy and the main economic driver in many rural areas across the country. Approximately 75% of Canada's forested area lies in the boreal and forested tundra biomes, with the remainder including the extensive temperate evergreen forests of the British Columbia west coast, and some temperate deciduous forest regions in southern Ontario and Quebec which merge into the extensive hardwood forests of the north-eastern USA.

The forests of British Columbia are the most productive and typically located on hilly or mountainous terrain. Those near to the coast have been harvested extensively for well over 100 years, and many regions are now dominated by recently regenerated or actively growing second growth stands. Fire was undoubtedly an important disturbance agent prior to European settlement, but suppression of fires has been effective for most of the twentieth century, so that today harvesting is the major cause of disturbance on the coast. Exploitation of stands in the interior of B.C. was more recent, but most regions of the Province not lying in Provincial or National Parks are now under active forest management. Interior stands are generally less accessible and more susceptible to fires and infestations of insects such as mountain pine beetle.

East of the Rocky Mountains, the boreal and tundra ecosystems occupy an extensive and generally flat landscape, but are characterized by small-scale heterogeneity where microtopographic variations (often operating over distances of a few metres) create a vegetation patchwork of “upland” and “lowland” communities. In the western boreal, characterized by relatively low annual precipitation (typically >500 mm per year) the upland sites are typically relatively well-drained and dominated by pine, white spruce and/or aspen communities, which are frequently subjected to natural fires. These sites are typically more productive than the wetter lowland sites which often form shallow lakes or wetland areas surrounded by wet-site species such as black spruce and tamerack larch. The latter communities are somewhat less prone to fires, but stands are still typically replaced at intervals by aperiodic disturbance events. In the region of the Great Lakes and further east, annual precipitation is generally higher, so fires are somewhat less frequent but losses due to insect infestations (notably spruce budworm) are more significant. Much of the eastern boreal has been under some form of management for more than a century, whereas in the western boreal, large-scale forest management has been practised for less than 50 years. Hence, today, Canada’s boreal ecosystems are subject both to natural disturbance (mainly fire and insects), and increasingly to harvesting and other human activities (e.g., in Alberta, oil and gas exploration).

This brief review of Canada’s forests highlights the importance of disturbance—both natural and anthropogenic—as a crucial factor determining ecosystem dynamics. Hence any attempt to simulate ecological and economic impacts of climate change must take into account both the effects of climate on the natural disturbance regime and the human adaptive responses to these effects—which include removals and recruitment of productive timber stands in harvesting and management.

3.2 IBIS (Integrated BIosphere Simulator)

Development of the Integrated BIosphere Simulator (IBIS) is an ongoing project at the University of Wisconsin, Madison, under the leadership of Jon Foley. The general structure and philosophy of IBIS have been documented extensively in several papers by Foley and coworkers (e.g., see Foley et al. 1996; Kucharik et al. 2000). Hence the description presented here will be limited to the modification and application of IBIS to the specific problem of assessing impacts of climate change on Canadian forests and the linkage to an economic model.

3.2 IBIS Model Structure

Like other dynamic vegetation models (DVM), IBIS is a one-dimensional representation of vegetation processes that is normally run on a grid covering the region of interest. The model comprises several interlinked modules, each of which runs on its own appropriate time step. Hence interactions between the atmosphere and vegetation canopies, and internal canopy processes are typically simulated on hourly or shorter timesteps. Vegetation phenological processes (e.g., leafout and leaf fall) are driven by daily data, which are derived in turn from monthly input data using an internal stochastic weather generator. Net ecosystem production (NEP) is calculated on an annual time step, after annual net primary production (-NPP), soil respiration and disturbance effects are taken into account.

Climate variables needed to drive IBIS include: monthly mean values of daily temperature and temperature range (maximum – minimum); relative humidity; cloud fraction; total precipitation and number of days with precipitation; and wind velocity. Datasets for these variables have been constructed from Canadian national climate records. Scenarios of climate change, comprising the same set of climate variables, have been built from the output generated by recent GCM simulations (specifically transient mode simulations from the Canadian Climate Centre and Hadley Centre coupled models). In addition to climate data, soil texture information and digital elevation data are required and have been collected.

To provide regional- as well as national-scale simulations of climate change impacts, all data sets have been interpolated to a common 10 km grid using the Lambert Conformal Conic projection. This projection is preferable to the geographic projections often used in global scale simulations because it allows a more even distribution of grid points between northern and southern latitudes, and hence a better sampling of the land surface by the model. With a 10 km grid, the entire land area of Canada is represented by approximately 92,000 grid points. For many purposes such a large number is too expensive in computing terms, so aggregation of the 10 km data to lower resolutions is possible. It is anticipated that many simulations will be carried out at 20 or 50 km, but there will be the option of performing higher resolution runs on particular regions based on the same original data set when needed. Use of a non-geographic projection requires a small modification to IBIS, namely that grid cell coordinates (latitude and longitude) and individual cell areas are provided as additional inputs, and the source code must be modified to use these values in place of the values normally calculated from geographic grid coordinates.

IBIS is being used to model the present day distribution of forest vegetation across Canada, based on climatic, edaphic and elevational data sets. Work in progress includes comparisons of modelled fluxes of water, heat and carbon dioxide with eddy-covariance data obtained from sites in the boreal and coast forest regions. In a related study, we have compared modelled distributions of forest biomass and species composition (i.e., PFT distributions) with data obtained from Canada’s National Forest Inventory (CanFI) database. Initial results are encouraging, although we feel that better agreements are possible.

In particular, it is planned to compile a national database of regional mean natural disturbance return intervals as a means of estimating the frequency of disturbance for individual grid cells. Each grid cell will then have a prescribed disturbance interval that can be used to determine the age-class distribution of the vegetation. Structural attributes, including biomass density and fractional covers of overstorey and understorey components, can then be area-weighted to obtain a more realistic estimate of actual (rather than potential) mean values.

3.3 Simulation of disturbance effects on forest age-class distribution

Within IBIS, there were no specific representations of the effects of disturbances on the age-class structure of forested ecosystems; instead vegetation grew and adapted to the average environmental conditions found within a grid-cell and in the absence of change it will tend to an equilibrium state. Disturbances as implemented in IBIS served only to reduce equilibrium values of structural variables such as biomass. Limitations to vegetation biomass and net primary production (NPP) are imposed by the physiological and phenological characteristics of those PFTs determined to be able to exist, and by the effects of environmental variables (climate and soils). Yet, for most of the natural forested ecosystems of the world, species successions interrupted by some form of ecosystem disturbance (either natural or anthropogenic) are the rule. In Canada, disturbances can have profound effects on the age-class structure of forests with important consequences for spatially averaged values of biomass and NPP (Kurz and Apps 1999?; Price et al. 1997).

In order to take proper account of these effects at the large scale, it is necessary to: (a) track the area fractions of each grid-cell disturbed each year; (b) update biomass density and other structural indicators for each fraction; (c) simulate growth of each fraction as a function of its age, structural characteristics and the current environmental conditions, and (d) perform areal summations over all age-classes to obtain grid-cell totals. With a model such as IBIS, it is necessary to repeat each of the first three steps for each PFT to determine the contributions of each to the age-class total.

In practice, given current computing constraints, such an approach is not feasible on a large scale and some compromises are required. For example, because boreal and temperate forests often reach ages in excess of 200 years, it would theoretically be necessary to track the growth of more than 200 annual cohorts for each PFT for each grid cell. In the modifications to IBIS discussed here a further fundamental approximation is made: it is assumed that NPP is age-independent and can be estimated simply from grid-cell averages of canopy characteristics (primarily leaf area index, LAI). This means that for each PFT, NPP is calculated from spatially averaged estimates of the structural factors, subject to the environmental conditions simulated for the year; NPP is then allocated according to the structural information stored for each age-class, and these factors updated for the next timestep.

The new disturbance module will calculate the fractional area of each grid cell burned annually (*fire*), and then transfer this fraction into a new 0-yr age vegetation cohort. For now, it will be assumed that fire is the only disturbance type to be considered. Once the mechanics for managing multiple age-classes have been developed and tested it should be possible to extend them to account for other disturbance agents.

Key assumptions

Calculations of canopy radiation interception in IBIS are performed separately for the vegetated portion within each grid cell (denoted by the fractional cover variables f_u and f_l, representing upper and lower canopies respectively), and a non-vegetated portion for each canopy. It is then assumed that differences in fluxes among different age cohorts are reflected by the area-weightings of their cover fractions. Moreover, it is assumed that performing a single set of flux calculations for the area-weighted average fractional cover will yield the same total fluxes as would a summation of the separate calculations for each age-cohort. Such an assumption has already been tested and found to work reasonably well for most circumstances. Interestingly, it fails in the boreal regions, with respect to surface runoff and drainage fluxes (and may therefore affect estimates of evapotranspiration (ET) and the canopy energy balance as well as NPP!). It is thought this is due to non-linearities introduced by snow melt, canopy interception of rainfall, or soil freezing and thawing (Ramankutty pers. comm. 1999).

Representation of age structure dynamics

In the new disturbance module, age structure will be considered only for upper canopy ("forest") PFTs: lower canopy PFTs (grasses and shrubs) are assumed to be short-lived compared to the forest types (although disturbances still affect both canopies). Hence in the following discussion, lower canopy dynamics will be omitted.

For each upper canopy PFT *m*, and each age cohort *n*, the rate of change in biomass (in carbon units), *dC/dt*, in a single IBIS grid-cell is given by

$$\frac{dC_{ymn}}{dt} = a_{ym} NPP_{mn} - \frac{C_{ymn}}{\tau_{ym}} - \left(\alpha_{yn}\, probf(n)\mathrm{P_D} + 0.005\right)C_{ymn} \tag{I1}$$

where a_{ym} is the current biomass of PFT *m* , and subscript *y* denotes a vegetation biomass compartment (with subscripts L, W or R, corresponding to leaves, wood or roots, respectively). The probability function $probf(n)$ determines how the annual grid cell area burned is distributed among the different age cohorts (initially assumed to be age-independent for Canadian ecosystems), where $\mathrm{P_D}$ is the exogenously determined probability of stand-replacing disturbance (including harvesting), and the coefficients α_L, α_W, and α_R define the fractions of biomass actually killed during disturbance (these values are uncertain: they will differ among disturbance types and regions, and may also be age-dependent). The constant 0.005 denotes the annual intrinsic mortality rate. For each canopy, changes in fractional vegetation cover must be updated each year to take account of the combined effects of growth, competition and disturbance:

$$\frac{df_u(n)}{dt} = \frac{df_u(t)}{dW(t)}\frac{dW(n)}{dt} - (\alpha_\mathrm{W}\, probf(n)\mathrm{P_D} + 0.005) f_u(n) \tag{I2a}$$

$$f_u(0) = 0 \tag{I2b}$$

where

$$\frac{dW(n)}{dt} = \sum_{m=1}^{8}\left\{a_{\mathrm{W}m} NPP_{mn} - \frac{C_{\mathrm{W}mn}}{\tau_{\mathrm{W}m}}\right\}$$

where $df_u(t)/dW(t)$ defines the rate of change of fractional cover with respect to carbon in wood (m^2 (kg C)$^{-1}$), in the absence of disturbance; and $\tau_{\mathrm{W}m}$ is the average turnover rate for woody biomass of PFT *m*. Note that each fractional area burnt is multiplied by the

PFT coefficient α_{Wm}, because only that fraction of woody biomass in the area assumed to be killed or removed. The remainder is considered to survive and may regenerate in following years.

The fractions of each grid-cell occupied by each age cohort are updated every year as follows:

$$fA_{veg}(0) = \sum_{n=1}^{N} \alpha_{\mathrm{W}}\, probf(n) \mathrm{P_D} \tag{I3}$$

$$fA_{veg}(n+1) = fA_{veg}(n) - \alpha_{\mathrm{W}}\, probf(n) \mathrm{P_D} \tag{I4}$$

where $\int_0^N fA_{veg}(n) = 1$

The grid cell average fractional covers, for the upper canopy, $f_u^* = \sum_{n=0}^{N} f_u(n) fA_{veg}(n)$, and for the lower canopy, $f_l^* = f_l$, are used to calculate the average fluxes for each PFT over each grid cell, including NPP, ET, sensible heat flux and soil water fluxes. Grid-cell average NPP is then distributed among the different age cohorts after some simplifying assumptions. Firstly, NPP can be expressed in a simple form as:

$$NPP = I_a \lambda_{\max} f_u \tag{I5}$$

where I_a is absorbed photosynthetically active radiation, PAR, and $I_a = I_0\left(1 - e^{-0.5LAI}\right)$, where I_0 is incident PAR, LAI is the one-sided Leaf Area Index, and $\lambda_{\max}$ is maximum Light Use Efficiency (LUE). At the grid cell level, total NPP for each PFT is estimated from

$$NPP_m^* = k_m\left(1 - e^{-0.5LAI^*}\right) f_u^* A_m \tag{I6}$$

where $k_m = I_0 \lambda_{\max}(m)$ is assumed to be independent of age, and A_m is the area fraction of the grid-cell occupied by PFT *m*.

Hence $$k_m = \frac{NPP_m^*}{\left(1 - e^{-0.5LAI_m^*}\right) f_u^* A_m} \tag{I7}$$

and for each age cohort, of each PFT,

$$NPP_{mn} = k_m\left(1 - e^{-0.5LAI_{nm}}\right) f_u(n) A_{mn} \tag{I8}$$

The area-weighted total $\sum_{m=1}^{M}\sum_{n=1}^{N}\left(NPP_{mn}\right)$ calculated in this way will not match the grid-cell NPP_m^*, however, because of age-dependent non-linearities in the flux and growth equations. To ensure consistency of these two quantities, both are calculated and used to obtain a grid-cell correction factor, *β(m)*, given by

$$\beta(m) = \frac{NPP_m^*}{\sum_{n=0}^{N} NPP_{mn}\, fA_{veg}(n)} \tag{I9}$$

and hence,

$$NPP_{mn} = \beta(m) k_m\left(1 - e^{-0.5LAI_n}\right) f_u(n) A_{mn} \tag{I10}$$

Model output

In its present form, IBIS can be used to generate numerous indicators, on daily, monthly and annual timesteps. Each output variable is written to a UCAR NetCDF format file, which allows convenient visualization both as dynamic maps (animated as time-dependent changes) and as complete time-series graphs for individual pixels. For the purposes of this study, the annual output of a few key variables is of greatest interest. These variables are: upper canopy aboveground woody biomass (which we will treat as an indicator of standing timber volume), annual net primary productivity (NPP, treated as an indicator of annual wood volume production) and dominant cover types (an indicator of species composition).

4 The Integrated Economy-Ecosystem Model: A Dynamic Forest/Agriculture Sector Model

There are several objectives in building the economic model. One is to forecast the economic effects of various climate change scenarios and their consequent impacts on Canada's vegetation. Changes in vegetation (distribution, species composition and productivity can all affect the economically optimal use of land—e.g., for agriculture or forestry—and hence land-use values. There is some evidence that these impacts might be quite large because some "equilibrium vegetation models" have predicted major shifts in location and area of some Canadian biomes (e.g., Rizzo and Wiken 1992; Lenihan and Nielson 1995). A second objective is to determine the possible implications for Canada's timber supply. While increases in temperature may increase forest growth and thus timber availability, there are other effects which may reduce growth responses or have negative consequences, primarily drought and increases in the frequency of natural disturbance regimes (e.g., Price et al. 1999; Bergeron and Flannigan 1995). A third objective is to determine the best adaptive responses to changes in climate and to understand the constraints that current land tenure systems and current forest public policies will impose on optimal adaptation (most of Canada's forest land is in public (state) ownership). Finally, a fourth objective is to understand what the welfare implications of ecosystem transition are to Canada's rural communities and the forest products industry, as well as to the national socio-economic framework.

Achieving these objectives requires a linkage between a dynamic economic model and the DVM. As outlined in the previous section, IBIS is the DVM that will be used in this study. In this section we describe the economic model, which is a dynamic partial equilibrium model of the type used by Sohngen and Mendelsohn (1999). This type of economic model is difficult to integrate directly with most ecological models, however, because the models have inherently different structures. Economic models usually have an optimization model at their core, while ecological models such as IBIS are typically process models. Because a large number of alternative scenarios need to be specified and simulated in an optimization model before the optimum solution is found, there are restrictions on the amount of detail that can be carried from the process model into the optimization model.

4.1 Technical Description of the Integrated Economic/Ecosystem Transition Model

In this section we describe a formulation of a model of Canadian forest sector and agricultural land values. Once the description of this formulation is completed it should be relatively easy to describe how the linkage between IBIS and the economic model is accomplished.

We begin by describing the dynamics of the forest system and by defining some terms. The model will track the areas of different forest types, *m*, age classes, *n*, in economic regions, *j*, during each annual period, *t*, of a 200-year time horizon. This will be denoted, A^F_{mntj}. The area of forest land (of type *m*, age class *n,* in region *j*) that advances to the next age class, *n*+1, from period *t* to period *t*+1, depends on a number of factors and is described by a forest transition equation (E1). One of these factors is the area harvested in period *t*, denoted $h_{m'nmjt}$. Here, *m'* denotes the original forest type and *m* denotes the forest type after harvesting and regeneration. The transition equation also depends on any natural transfers from other forest types(e.g., due to changes in natural succession) and on losses due to areas converted to agriculture, h^A_{mnljt}. The transition equation is:

$$A^F_{m,n+1,j,t+1} = \left(A^F_{mnjt} - \sum_{k=1}^{M} h_{mnkjt} - \sum_{l}^{L} h^A_{mnljt} \right) \theta^{mn+1}_{mnjt} \qquad \text{for all } m,n,j,t \qquad \text{(E1)}$$

(where superscripts *F, A* denote forest and agricultural land respectively). The term θ^{mn+1}_{mnjt} describes disturbance regimes. Specifically, θ^{mn+1}_{mnjt} is the proportion of land of forest type *m*, age class *n*, in region *j*, and period *t,* that advances to age class *n*+1 in period *t*+1. The term $\theta^{m'0}_{mnjt}$ is the particular disturbance parameter which describes how disturbances such as fire and insects transform forest areas of type *m*, age class *n* to type *m*', and age class 0, where *m*' denotes one of several forest types. The sum of these parameters should equal unity for each region *j* and period *t*:

$$\theta_{mnjt}^{mn+1} + \sum_{m'=1}^{M} \theta_{mnjt}^{m'0} = 1 \qquad \text{(E2)}$$

Another transition equation is required to describe how the youngest age class changes from one period to the next. This is:

$$A_{m,0,j,t+1}^{F} = \sum_{m'=1}^{M} \sum_{n'=1}^{N} \left\{ \left(A_{m'n'jt}^{F} - \sum_{k=1}^{M} h_{m'n'kjt} - \sum_{l=1}^{L} h_{mn'ljt}^{A} \right) \theta_{m'n'jt}^{m0} + h_{m'n'mjt} \right\} + \sum_{l}^{L} x_{lm'jt}^{F} \qquad \text{(E3)}$$

This equation contains several components. First, areas left after harvest of each forest type *m*' and age class *n*' (including type *m*) may be subject to disturbance regimes described by $\theta_{m'n'jt}^{m0}$ that result in a new stand of type *m*, age class 0. This is accounted for in the first set of terms under the first summation of the transition equation. Second, areas harvested in each forest type *m*' and age class *n*' may be transferred to forest type *m,* age class 0, depending on the harvesting/regeneration. This is represented by the terms $h_{m'n'mjt}$. Third, areas of agricultural land may be converted to agricultural land. Hence we introduce the variable x_{lmjt}^{F}, which is the area of agricultural land value class l converted to forest type *m*.

One final constraint that must be defined on the forest dynamics and harvesting side is that harvesting activity in any forest type *m* and age class *n* combination must be less than the area available:

$$\sum_{k=1}^{M} h_{mnkjt} + \sum_{l=1}^{L} h_{mnljt}^{A} \leq A_{mnjt}^{F} \qquad \text{for all } mntj \qquad \text{(E4)}$$

The model will also track the amount of land in agriculture and the transfer of land from agriculture to forest or vice versa. Hence, a transition equation for agricultural land is also required. This can be written:

$$A^A_{ljt+1} = A^A_{ljt} + \sum_{n=1}^{N}\sum_{m=1}^{M} h^A_{mnltj} - \sum_{m=1}^{M} x^F_{lmjt} \qquad \text{(E6)}$$

The equation says that the amount of land in agriculture value class *l* in region *j* in period *t*+1 is equal to the amount of land in that class in period *t* plus any transfers from forest land minus any transfers out of agriculture.

This completes the description of the dynamics of land cover and land-use change. However, a series of other constraints remain to be defined. These include a constraint on the total forest harvest volume ($v_{mnjt}h_{mnjt}$) in region *j* which must equal the sum of volumes (V^T_{jikt}) shipped to each demand location *i*.

$$\sum_{m'=1}^{M}\sum_{n=1}^{N}\sum_{m=1}^{M} v_{m'njt}h_{m'nmjt} = \sum_{j=1}^{J} V^T_{jikt} \qquad \text{(E7)}$$

The variable V^T_{ijkt} is the volume transported from region *j* to demand location *i*, for production of product *k* in period *t.*

The model is driven by forest sector input demand for wood V^T_{ijkt} . Demand is specified as a downward sloping demand curve and the model objective function maximizes the sum of discounted consumer and producer surpluses. The objective function is:

$$\begin{aligned} \max \sum_{t=0}^{T} \Bigg\{ & \beta^t \sum_{k=1}^{K}\sum_{i=1}^{I}\left(R_{ikt}\left(\sum_{j=1}^{J} V^T_{ijkt}\right) - \sum_{j=1}^{J} C^T_{jikt}V^T_{jikt}\right) - \sum_{j=1}^{J}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{m'}^{M}\left(C^R_{mnm'jt}h_{mnm'jt}\right) \\ & \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{m'=1}^{M} C^F_{lm'jt}x^F_{lm'jt} + \sum_{l=1}^{L}\sum_{j=1}^{J} R^A_{ljt}A^A_{ljt} \Bigg\} \end{aligned} \qquad \text{(E8)}$$

The function $R_{ikt}\left(\sum_{j=1}^{J} V^T_{ijkt}\right)$ gives the benefits associated with the sum of all the wood shipped to demand location *i* from each region. The cost of transporting wood C_{jikt}^{T} from region *j* to demand location *i* is also included in the model. Hence, the first line of the objective function is the total benefit of wood product consumption minus the costs of transport. The second line of the objective function includes the costs of harvesting and regenerating stands, $C_{mnm'jt}^{R}$, the cost of transferring land from agriculture to forest and the $C_{m'ljt}^{F}$, and the rent derived from agricultural land R_{ljt}^{A}.

The model specified above is essentially a pure market model. In this form the model is applicable in the Canadian context, where large tracts of public land are managed under lease by forest products companies, only when the highly regulated policy environment is also modelled. A number of constraints imposed by the forest tenure system, including yield regulation, and land transfer and wood allocation restrictions, are also included to reflect the reality of forest management in Canada.

This model has several desirable characteristics. First, the model is dynamic and forward-looking and hence for a given climate change scenario, it can identify optimal timing of adaptation strategies such as land-use change, forest harvesting and forest regeneration options. Second, the model can serve as a forecast of ecosystem change with dynamic feedbacks between the economic agents that are manipulating the landscape and the changes in the ecosystem resulting directly from climate change. Hence, when forests are harvested, transitions to new forest types will be based on human activities that are linked both to the benefits for forest products as described by the demand system, $R_{ikt}\left(\sum_{j=1}^{J} V_{ijkt}^{T}\right)$; the costs of transporting, harvesting and regeneration; and on the climate linked potentials for forests to produce timber as described by $v_{m'njt}$. Land use transitions are also influence by the projected rents or land values associated of agriculture land R_{ljt}^{A} which are also influenced by climate change.

4.2 Calibration of Model to Saskatchewan

Saskatchewan was chosen as a test case and the model described in section 4.1 was calibrated to this province. Several methods were used to calibrate the model. This section will not contain comprehensive descriptions for all aspects of the model. Instead several important aspects relevant to the adaptive climate change aspects of this project will be described.

4.2.1 Specification of Model Regions (*j*)

The model described in section 4.1 is written as a spatial model and may contain several regions. In calibrating the model for Saskatchewan, census regions and vegetation types from the Canadian National Soil Database were used to create regions. The attributes used to create regions are shown in Table 4. There were 6 census regions and 7 vegetation codes used, for a potential total of 42 separate regions. The southern census regions of the province were aggregated into one region because there is little forest land in the south. This left 4 regions that spanned the province in the transitions zone between prairie and forest and 1 large northern region that occupies mostly forested land (See Figure 4). Vegetation types are shown in Figure 5. The regions are developed by overlaying the map of census regions in Figure 4 with the vegetation codes in Figure 5.

Table 4. Region attributes.

Census Region	Vegetation
4713	Agriculture
4714	Coniferous
4715	Deciduous
4716	Grassland
4717	MixedForest
4718	Parkland
	Others

Figure 4. Saskatchewan Census Regions used in the Agriculture/Forest Sector Model

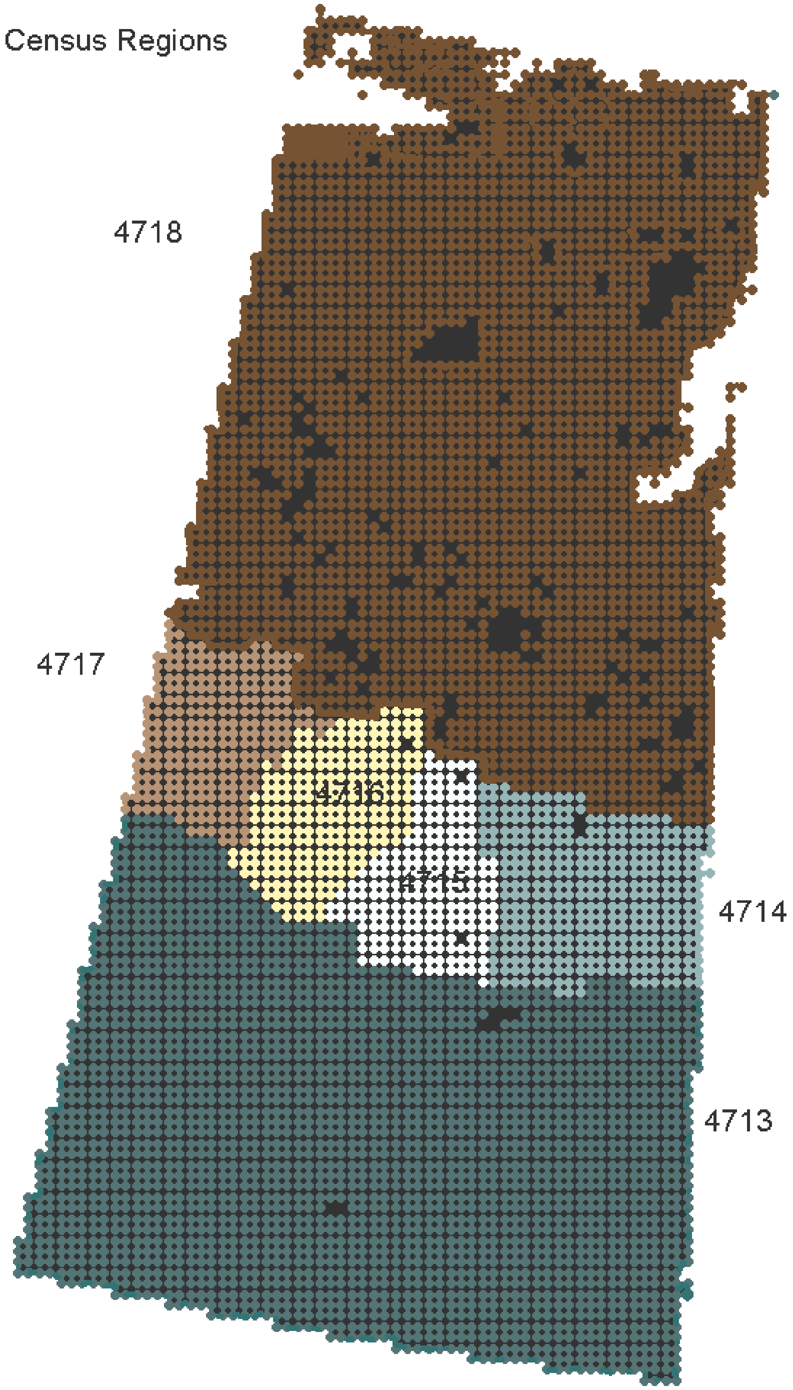
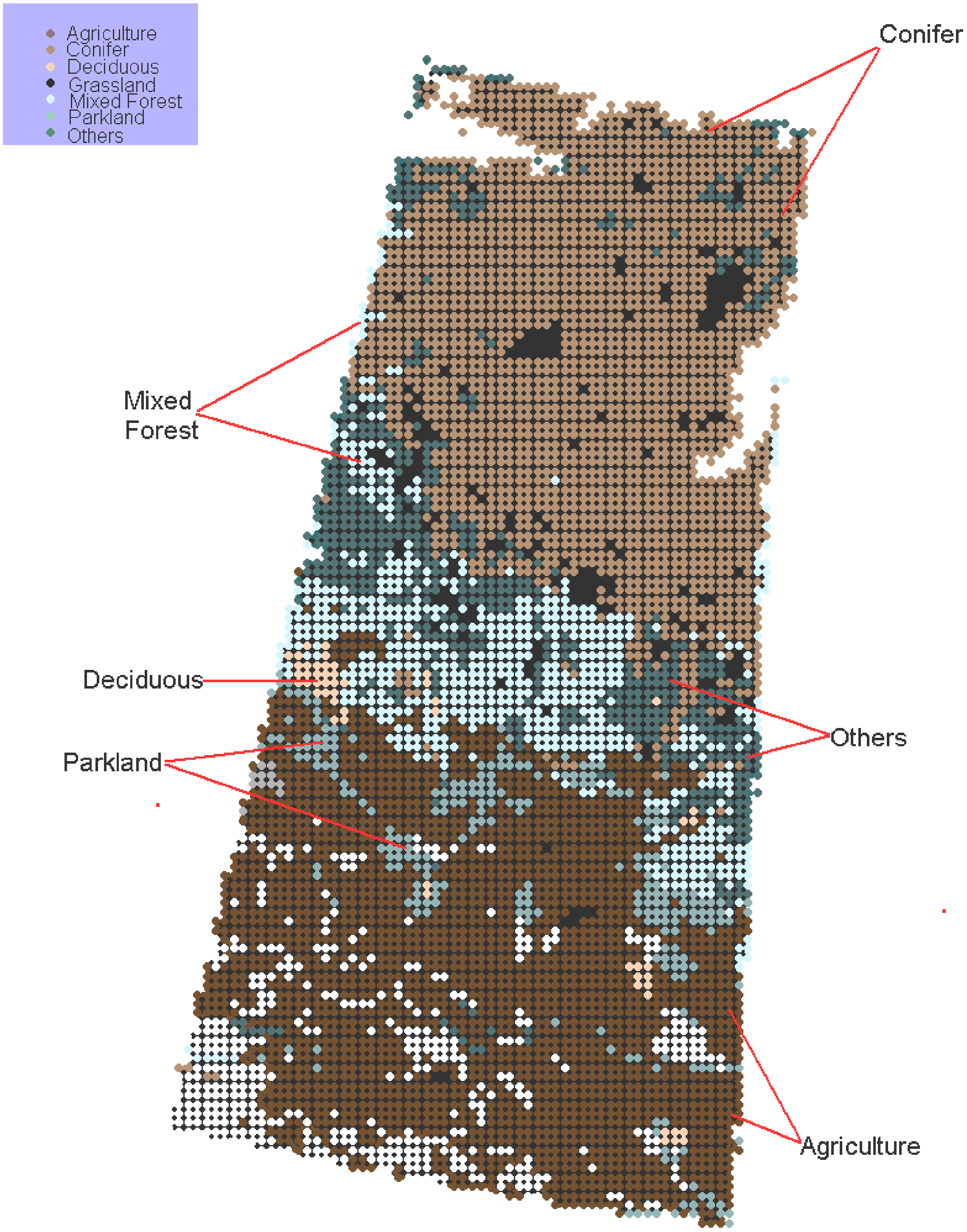


Figure 5. Vegetation Types of Saskatchewan from National Soil Database



4.2.2 Calibration of Agriculture land rents $\left(R_{ljt}^{A}\right)$

Agriculture land rents were estimated by using the model described in section 2 to project agriculture land values into the future and onto land currently occupied by forest land (Potential Agriculture Land Values). This required using the same climate change scenario as that used in section 2 to project agriculture land values on current agriculture land, namely the scenario based on the CGCMII model developed by the Canadian Centre for Climate Modeling and Analysis (CCCma). Other data requirements included soils data for current forested lands, which was obtained from the Canadian National Soil Database. The soil and climate data were available in the 20x20km grid cells described earlier. This was used to estimate potential agriculture land values that were linked to both climate changes and soils. The magnitudes of potential agriculture land values in the forested areas were limited by the forest soils as shown by the coefficients for forest soils in table 2. The estimated agricultural land values were overlain with the region definitions describe in section 4.2.1 to develop a curve for potential agriculture land values for each regions, which were in most cases composed of more than one 20x20km grid cell.

When the agriculture land values model is used to project land values onto existing forest land the resulting values represent potential agriculture land values only. These are only potential values because these values would only be realized if the land was converted from forest land. Conversion may not occur because the land is more valuable as forest land or because there are other barriers to conversion. Figures 6 to 8 show potential land values and areas in the northern census region for the current conifer, mixed and other vegetation types. Agriculture land potential for land values greater than $0/ha for the conifer group is in the range of 800,000 to 900,000 ha, which represents about 17-19% of this vegetation type. If forest land is worth $1000 per ha this would be reduced to about 8-9%. For the mixed and other vegetation types the agriculture land potential for values greater than $0/ha is in the range of 520,000 ha and 390,000 ha respectively. This represents about 36% of the total area in the mixed type and 32% in the other vegetation. However, again these percentages are upper bound estimates of potential because

Figure 6. Potential Agriculture Land Values in Region Census 4718/Conifer Vegetation Type

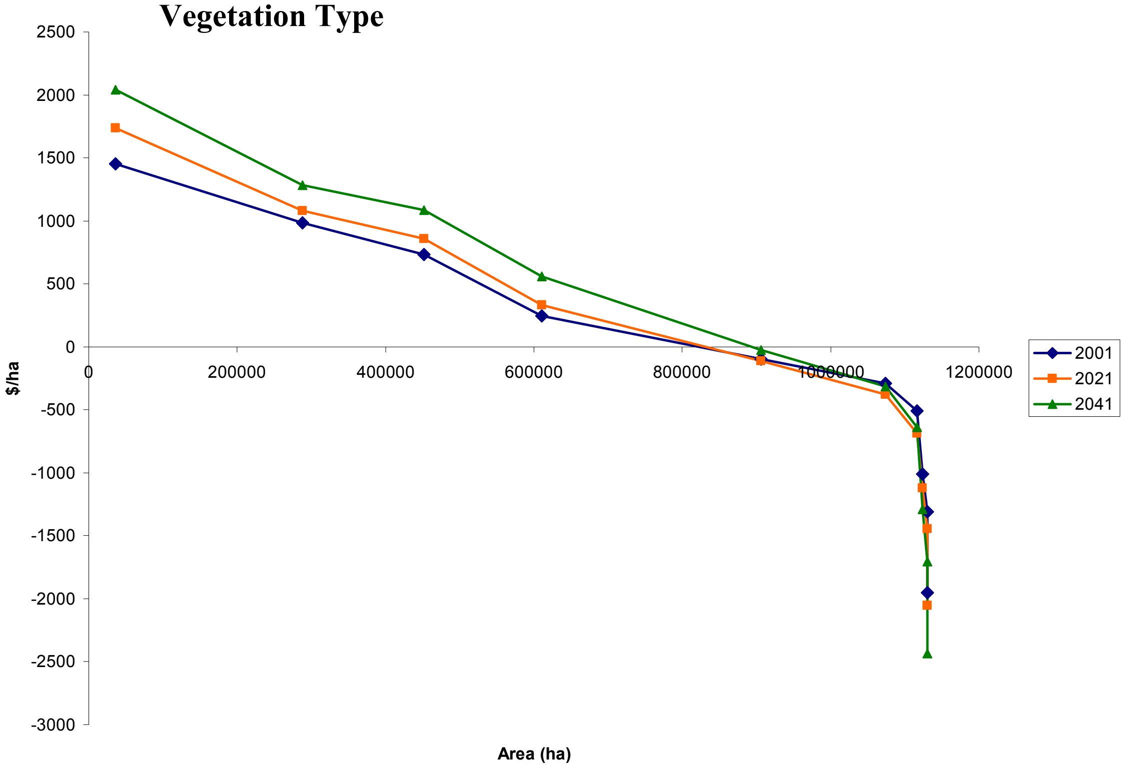


Figure 7. Potential Agriculture Land Values in Region Census 4718/Mixed Vegetation Type

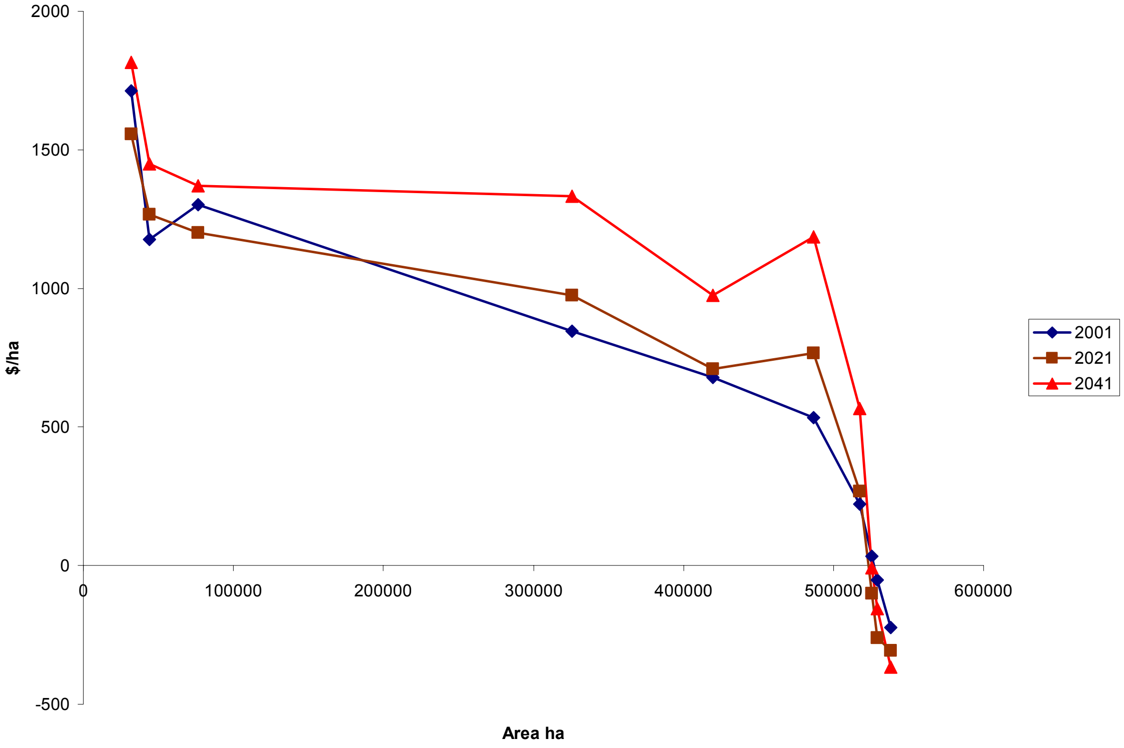
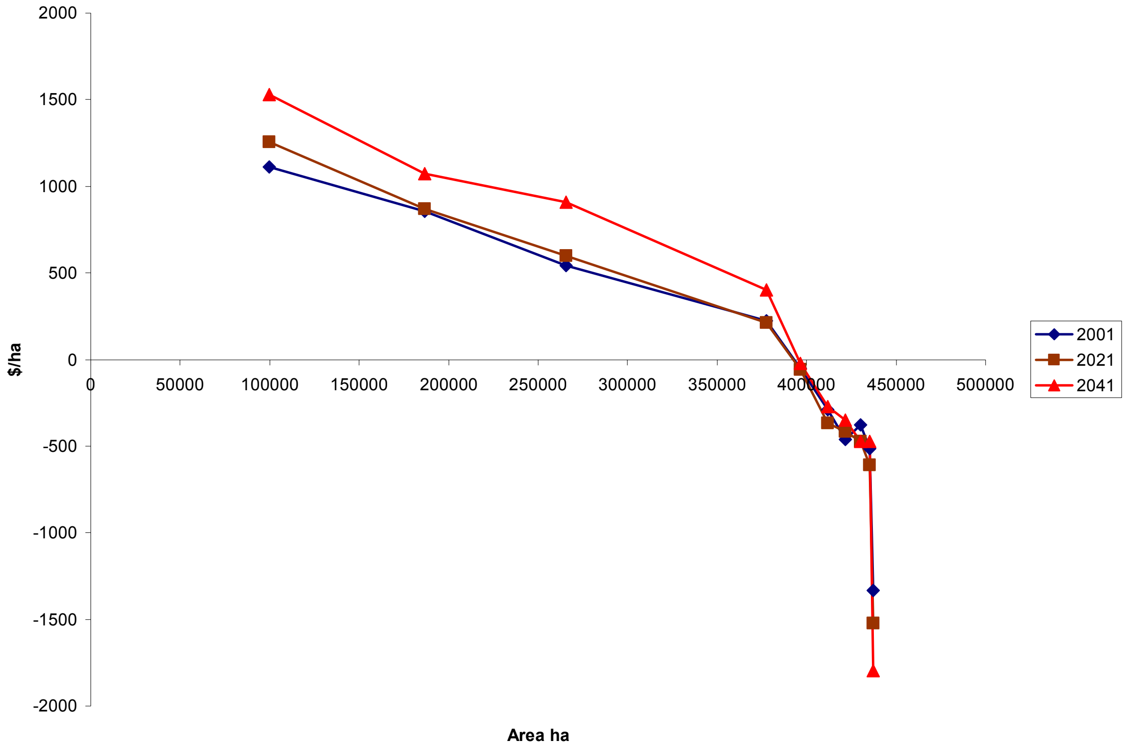


Figure 8. Potential Agriculture Land Values in Region Census 4718/Other Vegetation Type



estimates of forest land values are necessary to determine the value of the predominant competing land use. Climate change appears to increase the potential agriculture land values but does not appear to change the amount of potential land.

4.2.3 Calibration of Forest Age Class Distribution (A^F_{mntj})

The forest inventory for Saskatchewan was obtained from the National Forest Inventory Data base (Lowe, Power, and Gray 1996; Gray and Power 1997). Initial age classes were computed for each region by overlaying the inventory data on the on the 20x20 km grid cells.

4.2.4 Age and Climate Dependent Timber Volume Development Curves

Volume over age curves $\left(v_{m'njt}\right)$ for softwood, mixed and deciduous forest types were estimated based on volume data contained in the data base. These curves represent timber development, as related to age without climate change. Volume over age curves are also developed to account for responses in productivity to climate change. This was accomplished by using aggregated IBIS output for each region (as described in section 4.2.1) and observing changes in productivity trends for biomass.

Analysis of the IBIS output, shows significant changes in productivity after the year 2000. This is very apparent for northern region 4718/conifer vegetation type for conifer and deciduous species (see Figures 9 and 10). For stands originating in the years 1880, 1890 and 1900 the IBIS model forecasts increases in productivity in the year 2000, which is indicated by the increase in the slope of the biomass over age curve for both species. However for both deciduous and conifer species there appears to be some decreases in biomass productivity at least in some years. For example, when the year of origin is 2010, both species have smaller amounts of biomass per square meter.

The effects of climate change have varying effects depending on the region. For example, in Figure 11 IBIS output for deciduous species in region 4717/conifer exhibit declines in biomass starting in about 1960, for forest originating from 1880 to 1900. In addition, deciduous forest originating in years 2000 to 2020 exhibit much less biomass than older forest in this region. The conifer species show a similar pattern for (Figure 12) forest originating in years 2000 to 2020. Conifer forests originating in years 1880 to 1900, on the other hand, exhibit a slowing of growth around 1960 followed by an increase in growth which is then followed by a decrease in biomass around 2020. One possible explanation for the differences in productivity is related to moisture stress. Moisture is more limiting in the southern transition areas, such as in region 4717/conifer and hence increases in temperature actually increase moisture stress and result in dieback of older forest and inhibit growth of younger forest.

Figure 9. IBIS output for Boreal Deciduous Broadleaf Species for region 4718 census/Conifer. Graph shows biomass over age for 8 different years of origin.

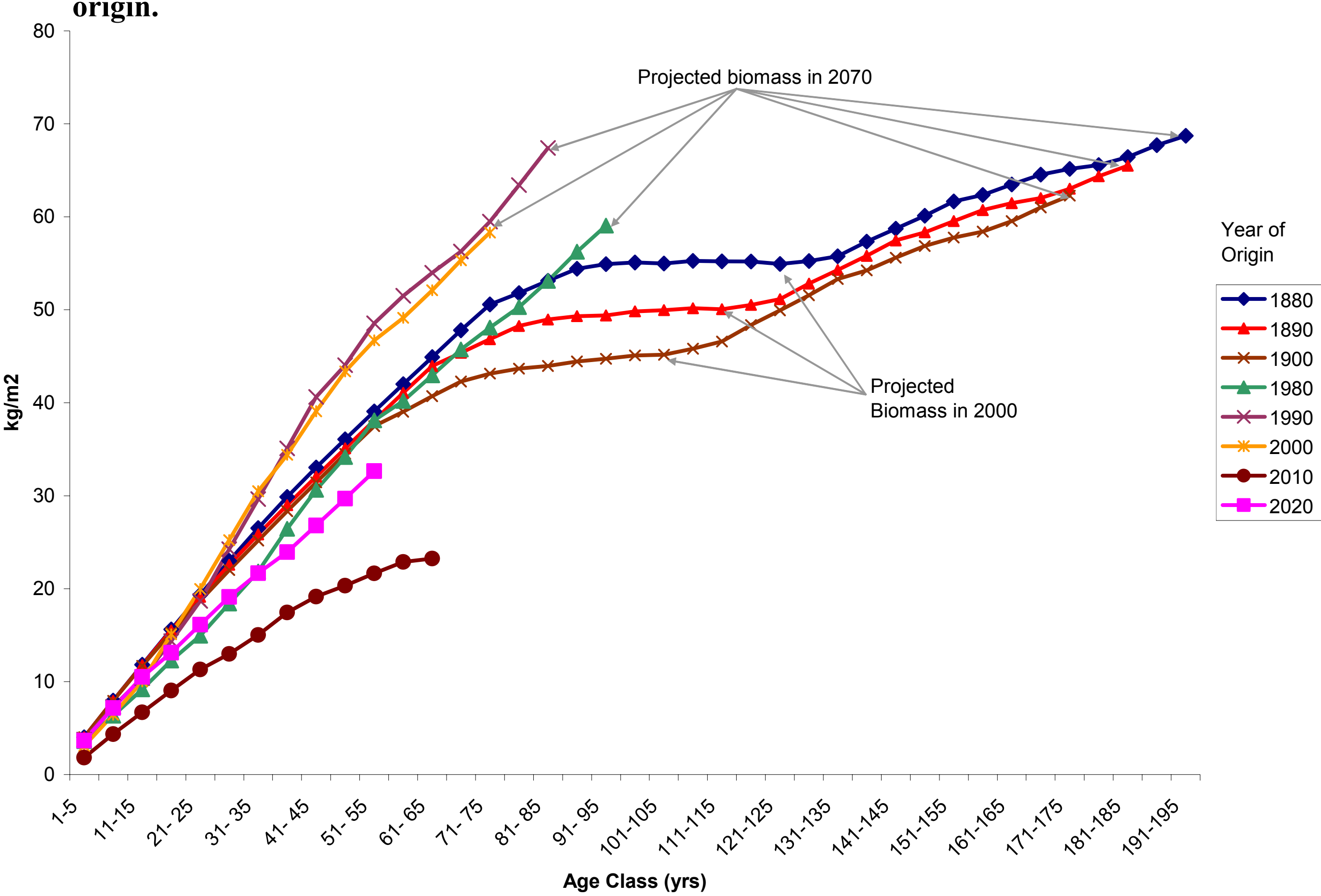


Figure 10. IBIS output for Coniferous Evergreen for region 4718 census/Conifer. Graph shows biomass over age for 8 different years of origin.

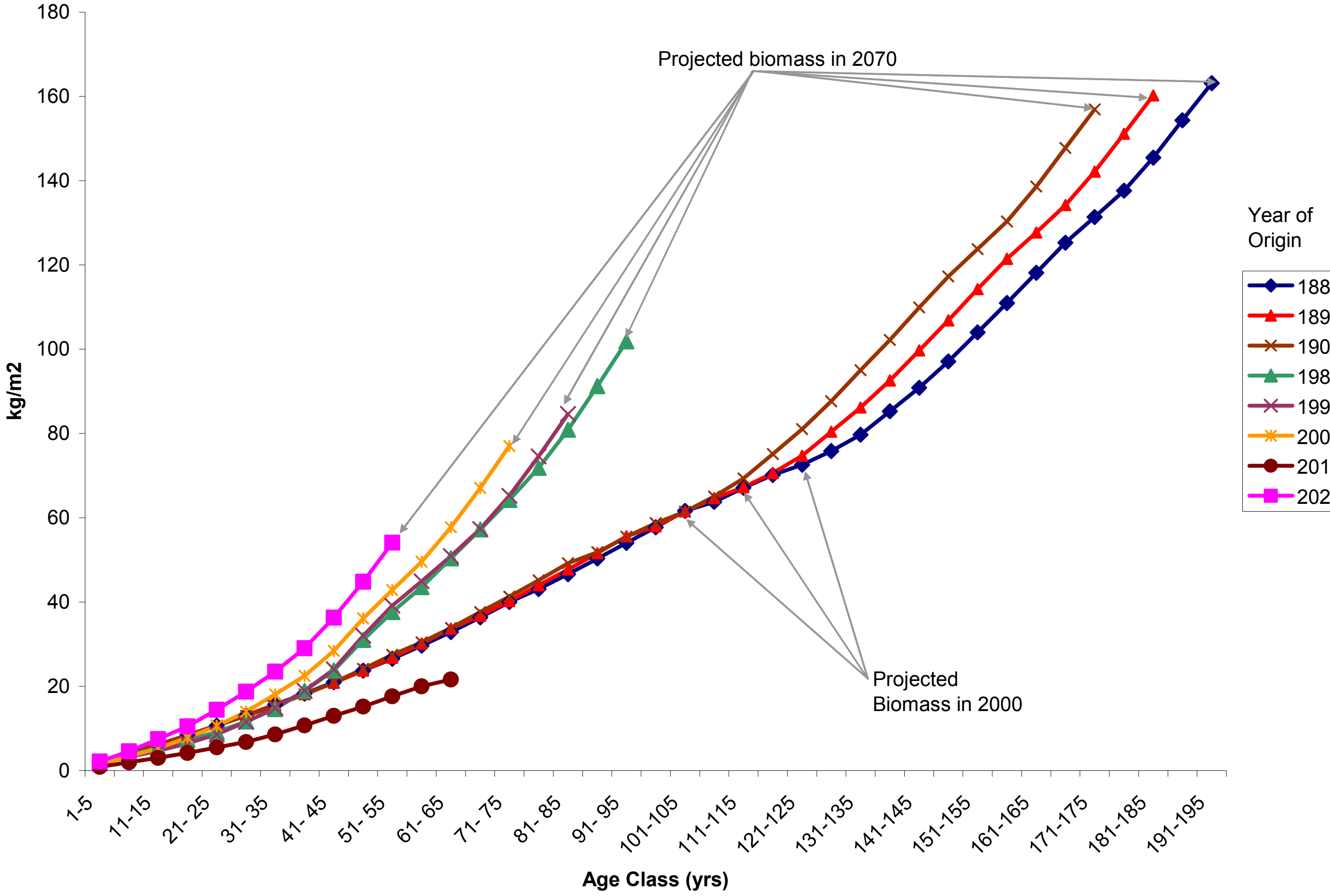


Figure 11. IBIS output for Boreal Deciduous Broadleaf Species for region 1417 census/Conifer. Graph shows biomass over age for 6 different years of origin.

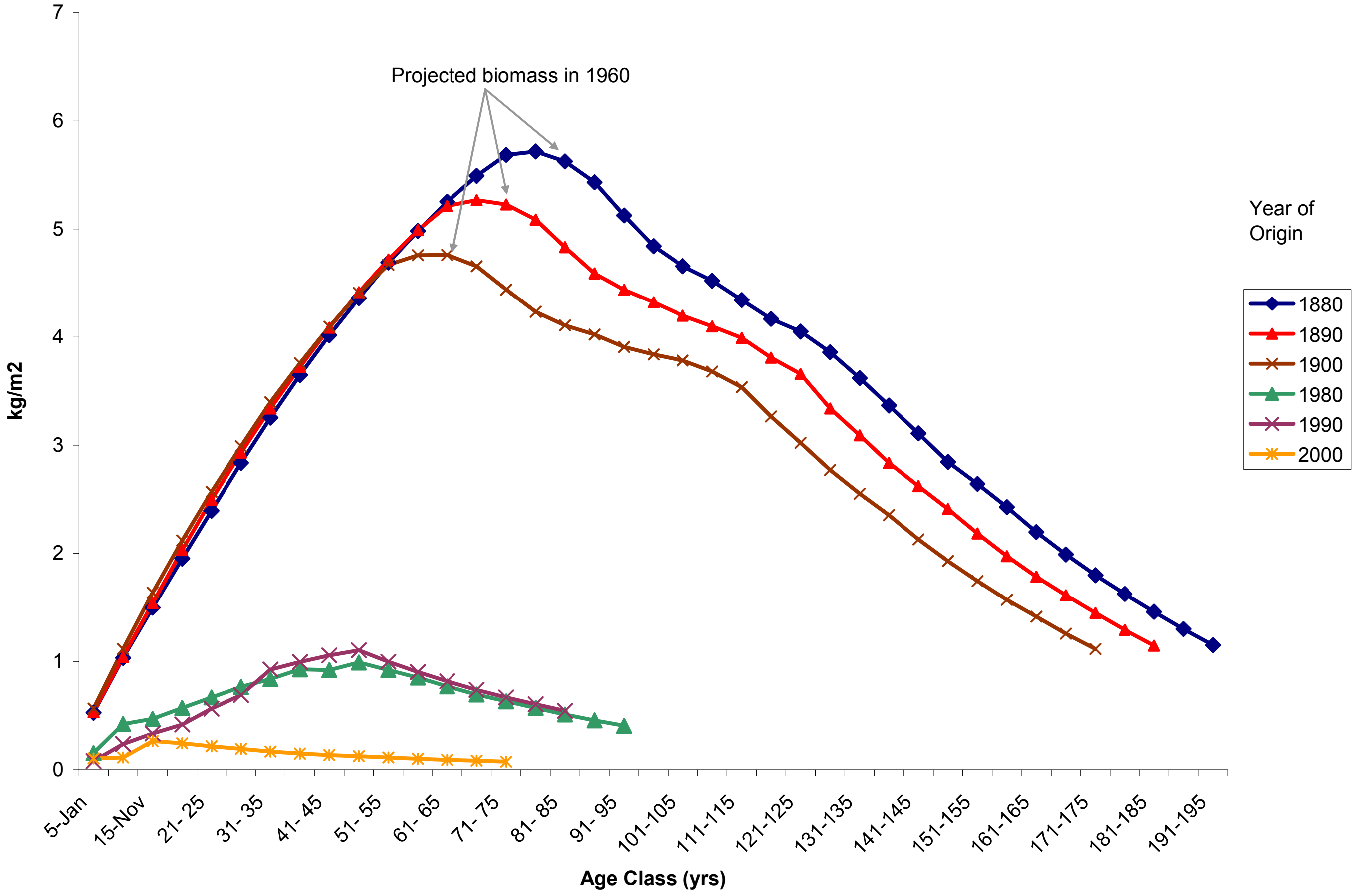
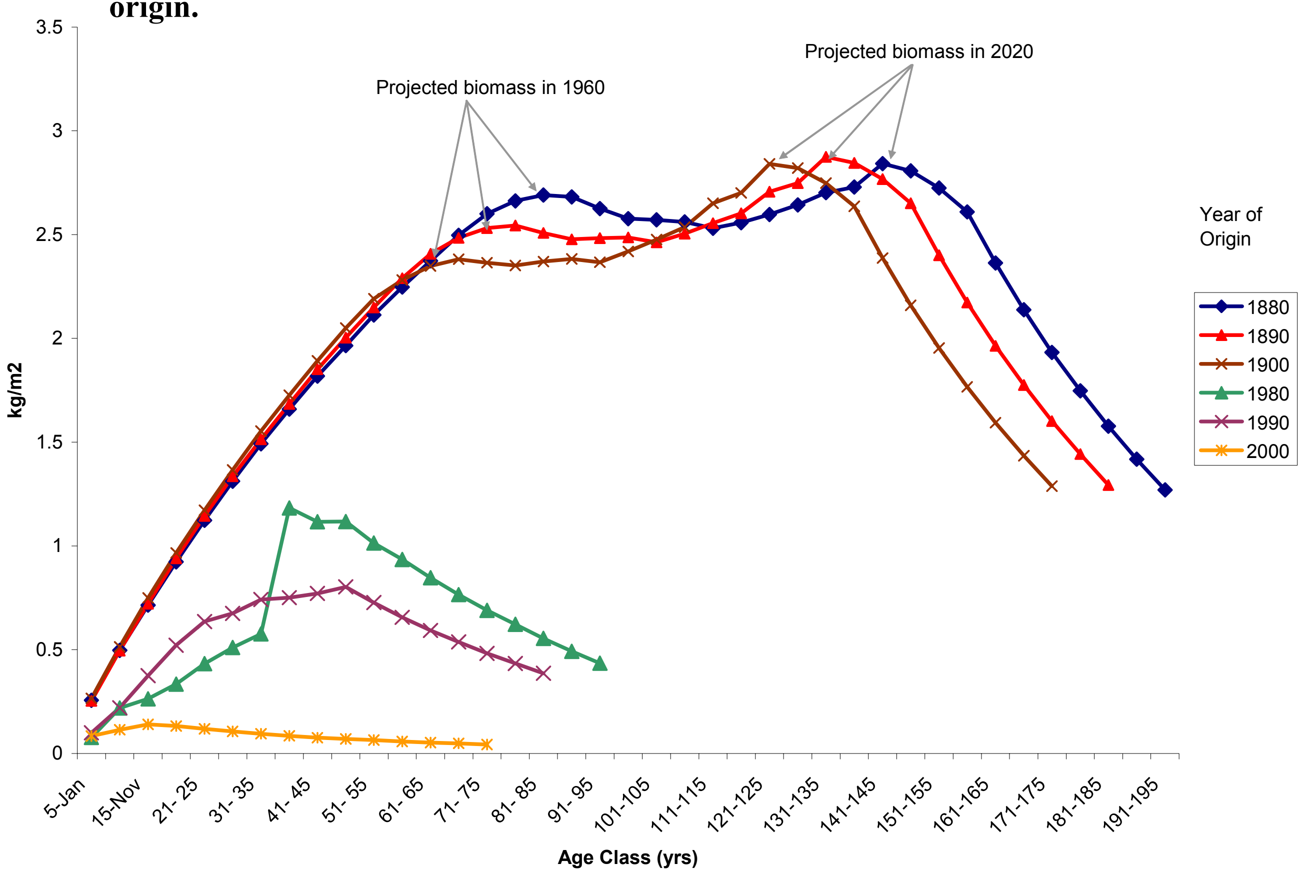


Figure 12. IBIS output for Boreal Conifer Evergreen Species for region 1417 census/Conifer. Graph shows biomass over age for 6 different years of origin.



The climate change induced changes in productivity for each region and species will be used in the integrated agriculture/forest sector market model in two ways. One is that adjustments will be made to volume over age curves derived from the inventory data to account for climate induced changes in productivity. A second way will be to convert the biomass estimates from IBIS into timber volumes and then substitute those into the integrated agriculture/forest sector market model. Solutions to the integrated sector model will then reflect both human and climate driven changes to the agriculture and forest systems.

4.2.4 Calibrating the Demand System for Wood Inputs $R_{ikt}(\ )$.

The forest sector portion of the integrated market model is driven by the demand for wood inputs at demand locations in Saskatchewan. Figure 13 illustrates the demand locations in relation to a road map of the province. The model formulation maximizes the benefits of using the wood inputs minus wood costs. Benefits are represented by the area under the demand curve. The wood input demand curves were derived from estimated systems of input demand functions for softwood and deciduous species for both the Pulp and Paper Sector and the Wood Industries. Statistics Canada Data was used to estimate these input demand functions. Harvest costs were based on averages estimated from Statistics Canada's Logging Industry Data.

4.3 Discussion

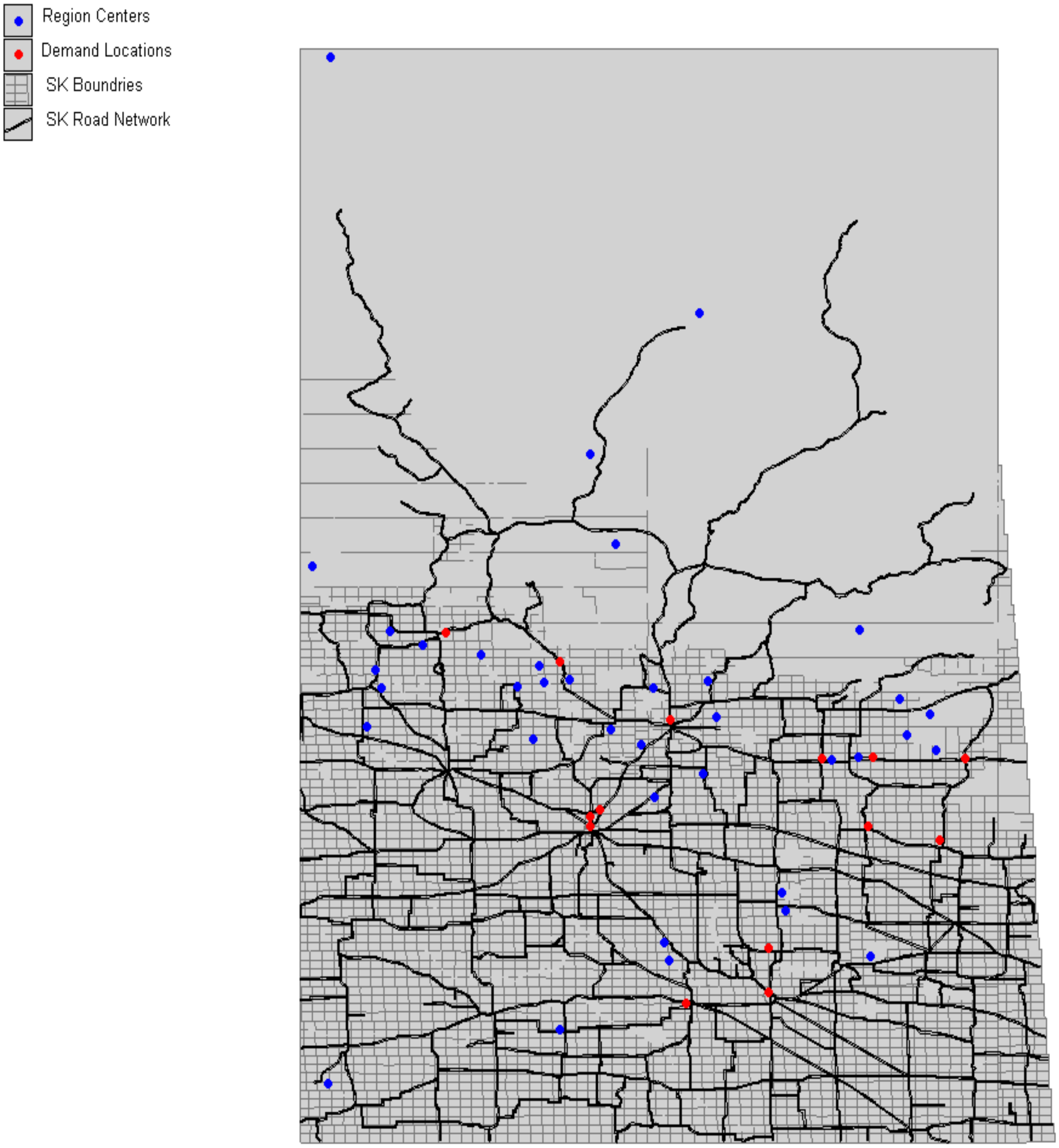
The integrated model described in sections 4.1 and 4.2 can be used to estimate both the impact of climate change (in terms of benefits and costs) on forestry and agriculture and the effects of climate change adaptation or not adapting to climate change. The model may also be used to assist in the development of adaptation strategies.

The costs and benefits of climate change will be estimated by comparing two different model runs. The base run is one in which agriculture land values and timber volume yield curves are not adjusted for climate change impacts. Optimal land use and land transfer (forest or agriculture), timber supply, total net benefits of agriculture and forestry activities will be derived for this scenario -- that assumes no change in climate. The second run will incorporate the climate induced changes in agriculture land values and changes in timber volume yield curves. The solutions to this second run will again be optimal in terms of land use, land transfer, timber supply and total net benefits, but this time anticipating changes in climate.

The difference in the net benefits associated with these two scenarios will give an estimate of the total net impact of climate change on the two industries as measured in dollars. The estimate will assume that forest managers, farmers and land owners anticipate climate change and complete adaptation within the available activities represented in the model. Comparison of the optimal activities for the two model solutions will provide a measure of adaptation. For example, it will be possible to compare land use transfers to agriculture from forestry and vice versa, with and without climate change. The effect of climate on timber supply could also be estimated by comparing timber supply from the two model runs.

The impact of incomplete adaptation could also be estimated by developing model runs that constrain the extent of adaptation. For example, if land use transfer is a major element of adaptation in the model solutions, then the effect of limits to land use transfer could be imposed by placing constraints on land use transfer within the model. In addition, the costs of constraints that may or may not be imposed by the policy environment can also be modeled and their costs estimated by comparing models with and without the constraints.

Figure 13. Demand locations and Region Centroids for Saskachewan



The calibration results described in sections 4.2.2 and 4.2.4, on agriculture land value projections and climate adjusted timber yield curves respectively, provide some clues to the results we can expect from the model. In the northern part of the province, it appears that the potential for agriculture because potential land values increased (See Figures 6, 7 and 8). All other variables held constant, this would tend to increase the amount of agriculture land in the north. However, it also appears that forest productivity will tend to increase overall. Hence, forest land values and agriculture land values will tend to change in the same direction. The amount of land transfer will then depend on the relative magnitude of land value changes in the two sectors. Hence, it is difficult to say what the direction of land use transfer will be without first running the integrated agriculture/forest sector model. In Region 4717, which is in the transition area between forest and prairie, forest land values are likely to decrease because of decreases in forest productivity (See Figure 11 and 12). If agriculture land values increase or stay the same in this region, then there is likely to be a transfer of land to agriculture in this region. More definitive results will be available once the runs of the integrated model have been made.

VIII. References

Bergeron, Y., Flannigan, M.D., 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. Water, Air and Soil Pollution 82, 437–444.

Foley, J.A., Prentice, I.C., Ramankutty, N., Levis, S., Pollard, D., Sitch, S., Haxeltine, A., 1996. An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. Glob. Biogeochem. Cycles 10, 603-628.

Kucharik C.J., J.A. Foley, C. Delire, V.A. Fisher, M.T. Coe, S.T. Gower, J. Lenters, C. Molling, J.M. Norman and N. Ramankutty, 2000. Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure. Global Biogeochemical Cycles 14(3), 795-825.

Kurz, W.A., Apps, M.J., 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecological Modelling 9, 526-547.

Price, D.T., Halliwell, D.H., Apps, M.J., Kurz, W.A., Curry. S.R., 1997. Comprehensive assessment of carbon stocks and fluxes in a boreal forest management unit. Can. J. For. Res. 27, 2005-2016.

Price, D.T., Halliwell, D.H., Apps M.J., Peng. C. 1999. Simulating effects of climate change on boreal ecosystem carbon pools in central Canada. *J. Biogeog.* in press.

Rizzo, B., Wiken. E., 1992. Assessing the sensitivity of Canada's ecosystems to climatic change. Climatic Change 21, 37-55.

Adams, R.M., McCarl, B.A., Segerson, K., Rosenzweig, C., Bryant, K.J., Dixon, B.L., Conner, R., Evenson, R.E., Ojima, D. 1999. "Economic Effects of Climate Change on US Agriculture," in *The Impact of Climate Change on the United States Economy*, ed. R. Mendelsohn and J.E. Neumann. Cambridge: Cambridge University Press.

Arthur, L.M. and Van Kooten, G.C. 1992. "Climate Impacts on the Agribusiness Sectors of a Prairie Economy," *Prairie Forum* 17:97-109.

Beattie, K.G., Bond, W.K., and Manning, E.W. 1981. *The Agricultural Use of Marginal Lands: A Review and Bibliography.* Ottawa: Environment Canada Lands Directorate.

Belsey, D., Kuh, E., Welsch, R. 1980. *Regression Diagnostics*. New York:Wiley.

Brklacich, M., Smit, B. 1992. "Implications of Changes in Climatic Averages and Variability on Food Production Opportunities in Ontario, Canada," *Climatic Change*, 20:1-21.

Brklacich, M., Stewart, R.. 1995."Impacts of climate change on wheat yield in the Canadian prairies," in *Climate Change and Agriculture: Analysis of Potential International Impacts*. Special Publication No.59, Madison Wisconsin: American Society of Agronomy.

Brklacich, M., McNabb, D., Bryant, C., Dumanski, J. 1997. "Adaptability of agricultural systems to global climate change: a Renfrew County, Ontario, Canada pilot study.," in *Agricultural Restructuring and Sustainability*, ed. B. Ilbery, Q. Chiotti and T. Ricard. Wallingford UK: CAB International.

Brklacich, M., Bryant, C., Veenhof, B., and Beauchesne, A. 1999. "Implications of gobal climatic change for Canadian agriculture: A review and appraisal of research from 1984-1997, " in *The Canada Country Study.* Ottawa: Environment Canada.

Bootsma, A. 1999. "A review of the impacts of climate variability and change on agriculture in Atlantic Canada," in *The Canada Country Study.* Ottawa: Environment Canada.

Canadian Institute for Climate Studies. 2001.Canadian Climate Impacts Scenarios (CCIS) Project. http://www.cics.uvic.ca/scenarios.

Centre for Land and Biological Resources Research. 1996. *Soil Landscapes of Canada v.2.2*. Ottawa: Agriculture and Agri-Food Canada.

Chapman, L. J. and Brown, D. M. 1966. *Climates of Canada for Agriculture: Canadian Land Inventory Report No. 3*. Ottawa: Department of Forestry and Rural Development.

Chiotti, Q., Johnston, T., Smit, B., Ebel, B. "Agricultural response to climate change: a preliminary investigation of farm-level adaptation in Southern Alberta," in *Agricultural Restructuring and Sustainability*, ed. B. Ilbery, Q. Chiotti and T. Ricard. Wallingford UK: CAB International.

Darwin, R., Tsigas, M., Lewandrowski, J., and Raneses, A. 1995. *World Agriculture and Climate Change: Economic Adaptations.* Agricultural Economic Report Number 703. Washington, DC: US Department of Agriculture.

Delcourt, G., and Van Kooten, G. C. 1995."How resilient is grain production to climatic change? Sustainable Agriculture in a dryland cropping region of Western Canada," *Journal of Sustainable Agriculture* 5 (3): 37-57.

Easterling, W.E. 1996. "Adapting North American agriculture to climate change in review." *Agricultural and Forest Meteorology* 80:1-53.

Environment Canada, Lands Directorate. 1976. *Land Capability for Agriculture.* Ottawa: Canada Land Inventory.

Grigg, D. 1995. *An Introduction to Agricultural Geography, 2nd Edition*. London: Routledge.

Lewandrowski, J. and Schimmelpfennig, D. 1999."Economic implications of climate change for U.S. Agriculture." *Land Economics* 75:39-57.

McCrae, T. and Smith, C. A. S. 2000. "Regional analysis of environmentally sustainable agriculture." in *Environmental Sustainability of Canadian Agriculture: Report of the Agri-Environmental Indicator Project.* ed. T. McRae, C.A.S. Smith, and L.J. Gregorich. Ottawa: Agriculture and Agri-food Canada.

Mendelsohn, R., Nordhaus, W. and Shaw D. 1994. "The impact of global warming on agriculture: a Ricardian analysis." *American Economic Review* 84:753-771.

Mendelsohn, R., Nordhaus, W. and Shaw, D. 1996. "Climate impacts on aggregate farm value: accounting for adaptation." *Agricultural and Forest Meteorology* 80: 55-66.

Mendelsohn, R., Nordhaus, W. and Shaw, D. 1999. "The impact of climate variation on US agriculture," in *The Impact of Climate Change on the United States Economy*, ed. R. Mendelsohn and J.E. Neumann. Cambridge: Cambridge University Press.

Mooney, S. and Arthur, L.M. 1990. "The impacts of climate change on agriculture in Manitoba," *Canadian Journal of Agricultural Economics* 38:685-694.

Price, D.T., McKenney, D.W., Nalder, I.A., Hutchinson, M.F., and J.L. Kestevan. 2000. "A comparison of statistical and thin-plate spline methods for spatial interpolation of Canadian monthly mean climate data," *Agriculture and Forestry Meteorology* 101:81-94.

Price, D.T., McKenney, D.W., Caya, D., and Cote, H. 2001. *Transient climate change scenarios for high resolution assessment of impacts on Canada's forest ecosystems.* Report to Climate Change Action Fund. Ottawa: Climate Change Action Fund.

Segerson, K., Dixon, B.L. 1999. "Climate change and agriculture: the role of farmer adaptation," in *The Impact of Climate Change on the United States Economy*, ed. R. Mendelsohn and J.E. Neumann. Cambridge: Cambridge University Press.

Singh, B. 1988. *Implications of climate change for natural resources in Quebec.* Climate Change Digest Series CCD88-08. Downsview, Ontario: Atmospheric Environmental Service.

Singh, B. and Stewart, R. 1991. "Potential impacts of a CO2 induced climate change using the GISS scenario on agriculture in Quebec, Canada," *Agriculture, Ecosystems and Environment* 35:327-47.

Singh, B., El Maayar, M., Andre, P., Bryant, C.R. and Thouez, J-P. 1998. "Impacts of a GHG-Induced climate change on crop yields: Effects of acceleration in maturation, moisture stress and optimal temperature," *Climatic Change* 38:51-86.

Smit, B. 1987. *Implications of climatic change for agriculture in Ontario.* Climate Change Digest Series CCD87-02. Downsview, Ontario: Atmospheric Environmental Service.

Smit, B. 1989. *Climate warming and Canada's comparative position in agriculture*. Climate Change Digest Series CCD89-01. Downsview, Ontario: Atmospheric Environmental Service.

Smit, B., Brklacich, M., Stewart, R., McBride, R., Brown, M. and Bond D. 1989. "Sensitivity of Crop Yields and Land Resource Potential to Climatic Change in Ontario, Canada," *Climatic Change* 14:153-174.

Smit, B. and Brklacich, M. 1992. "Implications of Global Warming for Agriculture in Ontario," *The Canadian Geographer* 36:75-78.

Smit, B, McNabb, D. and Smithers, J. 1996. "Agricultural adaptation to climatic variation," *Climatic Change* 33:7-29.

Statistics Canada. 1996a. *1996 Census of Agriculture*. Ottawa: Statistics Canada.

Statistics Canada. 1996b. *1996 Census of Canada*. Ottawa: Statistics Canada.