Predicting the Impact of Climate Change on Fragmented Prairie Biodiversity: A Pilot Landscape Model

Final Report to The Climate Change Action Fund

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  Projected Climatology B Temperature change factors
  Projected Climatology B Precipitation change factors
  Projected Climatology B Evapotranspiration change factors

Background

The issue of global climate change is moving to the forefront of national policies throughout the world. Its potential impacts on prairie biological diversity in Canada have recently been reviewed by Anderson et al. (1999), Clair et al. (1999) and Herrington et al. (1997). For aquatic systems, wild species tied to semi-permanent or seasonal wetlands are predicted to be the most affected by climate change in this region. In addition, major consequences for some fish species due to increases in water temperature and salinity are also predicted. Indeed, the fish community has been suggested as being an indicator of many of the impacts of climate change (Herrington et al. 1997). For terrestrial systems, a number of potential impacts on biodiversity and wildlife have also been identified (Anderson et al. 1999, Herrington et al. 1997).

The persistence of a particular species in a warmer, drier climate lies in its ability to adapt to the new ecological regime. The easiest way for a species to adapt is to shift its geographic range to a new area that has the appropriate climate (Hunter 1996). However, this may not be as easy as in the geologic past for two reasons. First, current populations of many native species are already stressed by competition with exotic species, mortality from pesticides and pollution, and the effects of overexploitation (Hunter 1996, Meffe and Carroll 1994). Because stressed populations tend to be small and produce few offspring, they have a reduced ability of dispersal into a new habitat.

Successful dispersal is a prerequisite for a species shifting its geographic range in response to climate change. Second, human alteration of landscapes has reduced the total amount of suitable habitat for many species and fragmented these landscapes with roads, dams, croplands, and urban areas. Thus, the odds of a dispersing individual being able to arrive in a suitable habitat have been much reduced (Gates 1993, Peters and Lovejoy 1992).

The prairies of Canada are one of the most altered and highly fragmented ecosystems of the planet (Samson and Knopf 1996). Recent research conducted in Saskatchewan dramatically illustrates the challenges facing both terrestrial and aquatic prairie biodiversity in dispersing to new habitats. For example, native grassland beetles and spiders show a typical species richness/area relationship with greatly reduced richness on smaller pastures. Analysis of satellite vegetation cover maps has shown that 99% of remaining native grassland patches are of relatively small size (James et al. 1999; Fig. 1). Furthermore, an analysis of rarity in arthropods has shown that only a few native species are widespread, and that 45% and 36% of beetle and spider species respectively were recorded only once or twice. Aquatic ecosystems are also highly fragmented (Fig. 2). For example, research on one prairie watershed revealed 47 barriers to fish passage and that the watershed had been fragmented into 16 separate artificial >watersheds= as a result. In that watershed, northern pike spawning habitat had been reduced by 75%, one fish species has been eliminated from the system, and another is believed to be at risk (K. Murphy, unpubl.).

In addition, some site-specific surveys have been conducted that help to build a more accurate picture for particular areas. For example, Saskatchewan Wetland Conservation Corporation=s native prairie stewardship program has surveyed areas of the Regina Plains to determine the extent of remaining native grassland (Riemer et al. 1997). They found that only 16% of sites surveyed could be considered as native grassland, most were less than 80 acres in size, and only 3% of the remaining native prairie sites that they surveyed were in very good to excellent condition.

In summary, it is clear that a large number of terrestrial and aquatic species on the highly fragmented prairies are at risk of extirpation through the effects of climate change. The assumption has been that, under climate change, they will move and that others will take their place (Clair et al. 1999, Anderson et al. 1999). The reality may be quite different.

Targets, Goals and Objectives

The goals of this research project are to predict the impacts of climate change on terrestrial prairie biodiversity and to evaluate various adaptation strategies to offset these impacts. The research program addresses a number of gaps in our knowledge of impacts of, and adaptation to, climate change on the prairies (summarized in Anderson et al. 1999, Clair et al. 1999, Herrington et al. 1997) including: very little baseline knowledge of highly diverse taxa; uncertainty as to response of ecological communities; lack of integrative studies of ecosystem-level behaviours; lack of modeling terrestrial and aquatic impacts; and lack of studies of effects on prairie wildlife and biodiversity. Our research is being conducted relative to a nationally standardized ecological classification framework (Acton et al. 1998, EWSG 1995). Within that ecological framework, the specific objectives of this research project are to:

1) Develop an index of landscape ecological integrity based, among other things, on measures of terrestrial and aquatic habitat loss and fragmentation;

2) Classify and prioritize prairie watersheds for adaptation actions according to this

index;

3) Review the annual dispersal capabilities of various plants and animals based on their mobility as individuals and as well as between their generations;

4) Develop an ecosystem-based pilot model (e.g. Bunce & Howard 1990, Bartlein et al. 1997, McDonald & Brown 1992, Root & Schneider 1993, Scheel et al. 1996) that predicts how local and regional taxa will disperse in relation to climate-induced ecosystem change; and

5) Discuss potential adaptations that could offset these impacts.

The project used existing comprehensive data sets for the Saskatchewan prairies including recently derived vegetation and water cover (from satellite imagery at 1:50,000 scale), soils data, ecological classification digital data, hydrological data, species distributions, and data on human infrastructure (e.g. roads, population centres, cadastral data). Combining staff and computer resources from SERM and the University of Regina, these data were integrated within ESRI Corporations Arc/Info GIS to establish spatial relationships. In a related project, analyses of spatial relationships are being conducted using the FragStat (Berry et al. 1998, McGarigal and Marks 1993) computer program for measures of fragmentation and dispersal.

Relevance

SERM is a member of the Prairie Adaptation Network and other climate change initiatives which will inform its members of impacts and adaptations throughout the prairie provinces. The project itself will have at least two other major >plug-ins= to ensure its successful dissemination to stakeholders. First, both SERM and CPRC are partners in the new Saskatchewan Prairie Conservation Action Plan (PCAP, 1998), a partnership which includes the Canadian Wildlife Service, Ducks Unlimited, Parks Canada, Grazing and Pasture Technology Program, Nature Conservancy Canada, Nature Saskatchewan, PFRA, Saskatchewan Agriculture and Food, Saskatchewan Energy and Mines, Saskatchewan Research Council, Saskatchewan Stock Growers= Association, Saskatchewan Wetland Conservation Corporation, University of Saskatchewan, and World Wildlife Fund Canada. Second, SERM is coordinating the production of the new Saskatchewan Biodiversity Action Plan (SERM, 1999) whose partners include SaskEnergy, SaskPower, SaskWater, Saskatchewan Departments of Agriculture and Food, Economic and Cooperative Development, Energy and Mines, Inter-governmental and Aboriginal Affairs, Municipal Affairs, Northern Affairs, Highways, and Saskatchewan Wetland Conservation Corporation. These numerous linkages will ensure that the results of this project will be widely distributed throughout the province and adjacent regions.

Watershed Classification

The basis for this clustering exercise was the PFRA watershed map of Saskatchewan. The aggregated historic and current watersheds were the result of a visual clustering exercise using overlays of relevant information and data. Numerical analysis was not performed since numerical data does not exist for each watershed in the PFRA base map. Overlays included total dissolved solids (TDS), ice-free, glacial, and zoogeographic data. Use of these data sets is fairly self-explanatory except, perhaps, for TDS. TDS was selected for the following reasons: it approximates the geochemical nutrient input of the watershed and thus ties in the terrestrial enduring features (soils); a province-wide data set was available; and TDS has been used in Saskatchewan as an analog of ecological productivity for several decades (Chen 1992).

The resulting aquatic ecological regions map (Fig. 3) represents the most likely, biologically relevant, clustering of watersheds prior to 1850. This year was selected *a priori* as one pre-dating major European settlement and the concomitant alteration of watercourses, water bodies, and watersheds.

In terms of the theoretical basis for ecologically relevant analysis and clustering, there are two differing views in the literature. One insists that terrestrial ecoregions are sufficient to explain the distribution of aquatic assemblages (Omernik 1995). However, Omernik (1995) does point out that more than watershed lines, such as soils and chemistry, etc. must be included in any analysis. A second view considers an analysis and grouping by hierarchical watersheds to be more relevant. This explains fish distribution (especially at regional levels) at least as well as terrestrial ecoregions do (Hughes et al. 1994). However, the correlation is poor at finer scales. At individual watershed levels the gradient, altitude, climate, etc. must be taken into account. The most comprehensive system for watershed clustering has been compiled by Maxwell et al. (1995). This system has been validated to an extent with native fish distributions (Nature Conservancy 1997).

The most comprehensive solution is the combination of the two approaches; the use of watershed lines with consideration of physiographic, geochemical, climatic, and zoogeographic information. This concept of regional watershed analysis does correspond to current distribution patterns and post glacial mechanisms of dispersal of all aquatic organisms, and not just fishes (Dadswell 1974, Wilson and Hebert 1998). This is the approach we adopted.

DATA SOURCES

1) *Saskatchewan Environment Watershed Map (ESQUADAT)*: Originally developed by the water quality agency of the day, being finalized in 1979. Adopted by SERM as the standard. Accuracy at roughly the 1:1,000,000 scale. Not available in digital form. Some paper copies within the department, especially in Environmental Protection Branch as this forms the basis for their water quality monitoring network planning. Not suitable from an ecological perspective (too few divisions and inaccurate).

2) *SaskWater Registrar's Management Map:* Based on the SERM standard but updated and revised by SaskWater. Standard SaskWater map for Registrar's purposes but not their most precise product. Accurate at the 1:1,000,000 scale. Available in digital form. Not suitable from an ecological perspective (too few divisions and inaccurate).

3) *Department of the Environment - Canadian Hydrographic Service Watershed Map:* Originally developed by DOE as part of their Canada-wide mapping system. Final corrections to paper charts in 1991. Scaled at 1:1,000,000, but not accurate. Available in digital form, digitized by Canadian Hydrographic Service. Suitable from an ecological perspective except for inaccuracy. First system to introduce standard nationwide coding.

4) *PFRA Watershed Boundaries for the Prairies:* Excellent, accurate, digital product. Selected by us as the basis for ecological work.

5) *Total Dissolved Solids*: Originally plotted by provincial fisheries staff in 1981. Not available in digital format. Map scanned from original and plotted by hand for rough clustering only.

6) *Glacial Hydrology*: Taken from the Atlas of Saskatchewan. Map scanned from original and plotted by hand for rough clustering only.

7) *Climatic Data*: Taken from the Hydrological Atlas of Canada. Map scanned from original and plotted by hand for rough clustering only.

Index of Ecological Integrity

A simple preliminary index of ecological integrity was developed for southern Saskatchewan building on Karr et al. (1986), Woodley at al. (1993), Minns et al. (1994), Hughes et al. (1998), and Moyle & Randall (1998). Virtually all human threats to biodiversity can be placed into one of four categories, which we term >The Four Horsemen of the Biotic Apocalypse= (James et al. unpubl.). The four categories are habitat loss and fragmentation, exotic species, pesticides and pollution, and over-exploitation. Measures from these impact categories can be combined to derive an index. We assumed that an ecosystem with completely intact integrity would score 100% and deducted points for measures of impact. The approach is simple but easy to understand for that reason. The important point is that the index is a *relative* measure of ecological integrity and not an absolute one. In theory, any measures can be used, but for simplicity we used five. They were:

1) The percentage of the ecosystem that is not in native vegetation from the Southern Digital Land Cover (SDLC). We defined >native vegetation= as woodland, shrub, wetland, or native grassland. This served as a general indicator of terrestrial habitat loss and fragmentation.

2) The percentage of the ecosystem that is cultivated for annual crop production from the SDLC. This served as a general indicator of fertilizers, pesticides and exotic species invasion.

3) Half of the percentage of the ecosystem that is converted to tame pasture (i.e. crested wheatgrass, brome grass, etc.) This served as a general indicator of exotic species invasion. We arbitrarily decided that tame pasture scored at a level of 50% of native vegetation in terms of its value to native biodiversity.

4) A ranked percentage of the ecosystem that is wetland from the SDLC if less than 5%. This served as a general indicator of aquatic habitat loss and fragmentation.

5) A ranked percentage based on the human population in urban centres within the ecosystem. This served as a general indicator of all ecological impacts.

The classified watersheds were laid over the SDLC and the analysis performed whereby the values of each measure were deducted from 100%. Each measure was arbitrarily assigned equal weighting in the index for each watershed, or 20% each. The results are shown in Fig. 3. It can be seen that the index of ecological integrity varied from 32 in the Moose Jaw watershed to 80 in the Turtle watershed. Based on these values, we chose two watersheds to serve as examples for the pilot model, the Moose Jaw watershed and the Frenchman watershed. The former is characterized by very low levels of native habitat and a high density of humans, whilst the opposite is true for the latter.

Plant and Animal Dispersal

A literature search covering the last 30 years was conducted for information relating to the dispersal strategies of various plants and animals. We were particularly interested in natal dispersal (birthplace to breeding place movements) rather than breeding dispersal (breeding place to breeding place movements) because the natal dispersal of a species is almost always much greater than its breeding dispersal. It is therefore much more relevant to our concern regarding the ability of species to move in response to climate change. The results are shown in Table 1 and represent information for approximately 250 species. These were used to judge the range of input dispersal values for the pilot model. It can be seen that annual dispersal distances vary over several orders of magnitude from very small movements in ant-carried seeds to much larger movements in birds.

Table 1. Annual Natal Dispersal Distances For Various Plants and Animals

Reference	Taxon (n)	Maximum	Mean	Median	Notes
Sutherland et al. 2000	Birds (77)	1.3-1305 km		0.03-10 km	
Sutherland et al. 2000	Mammals (68)	0.14-930.1 km		0.03-129.7 km	
Johnson 1988	Trees (3)	35-296 m		13-65 m	
Brunet et al. 1998	Herbs (49)	0-1.25 m			
Carey et al. 1993	Grasses (1)	1.1 m	0.19 m		
Stamp 1989	Grasses (4)		0.54-0.76 m		
Greene et al. 1999	Trees (1?)	150 m 15 m			Aspen Seeds & Clones
Govindaraju 1988	Trees (?)	25-122 m			
Dubbert et al. 1998	Insects (1)	150 m			
Broyles et al. 1994	Herbs/Insects (?)	1 km			Pollen
In Broyles et al. 1994	Herbs/Insects (?)	1300 m			Pollen
Stamp 1989	Grasses (1)	0.86 m	0.56 m		
Pleasants et al. 1992	Herbs (1)	4.5 m		1.0 m	
Nurmenium et al. 1998	Grasses/ Insects (1)	325 m			Pollen
Van Dorp et al. 1996	Grasses (6)	15-30 m			
Stewart et al. 1998	Trees (1)	200 m	10.8-24.2 m		
McEnvoy et al. 1987	Herbs (1)	14 m		2 m	

Webb 1987	Trees (2)	4 km			Via Birds
Stamp et al. 1983	Herbs (6)		0.24-3.29 m		
Cain et al. 1998	Herbs (1)	35 m			
In Cain et al. 1998	Herbs (4)	17-77 m			
In Cain et al. 1998	Herbs (?)	7.59 m	1.2 m		
In Cain et al. 1998	Trees (?)	150 m	16.1 m		
Zumr 1992	Insects (1)	1000 m			Natal?
In Zumr 1992	Insects (1)	19 km, 50 km			Natal?
Schultz 1998	Insects (1)	2000 m			Natal?
Gilbert et al. 1973	Insects (2)	450 m			Natal?
Crawley et al. 1989	Insects (1)	52 m	10 m		Larva
Antolin et al. 1987	Insects (2)	1 km			Natal?
Nason et al. 1996	Insects (1)	10 km			Natal? Tropical
Sutcliffe et al. 1996	Insects (1)	312 m			Natal?
Brookes et al. 1994	Insects (1)	260.8 m			Natal?
Haddad 1999	Insects (2)	935-5600 m			Natal?
Harrison 1989	Insects (1)	5.6 km			Natal?
Thomas et al. 1992	Insects (5)	1.0-8.65 km			Natal?
Hill et al. 1996	Insects	1070 m			Natal?

	(1)				
Conrad et al. 1999	Insects (?)	860 m			Natal?
McPeek 1989	Insects (4)	1000 m			Natal?
Michiels et al. 1991	Insects (1)	8 km			Natal?
Coombes et al. 1986	Insects (?)	200 m			Natal? Minimum
Hirth et al. 1969	Snakes (3)	1.0-3.6 km			Natal?
Gregory et al. 1975	Snakes (1)	17.7 km	4.3 km		Natal?
Baur et al. 1990	Molluscs (1)	14 m			Natal?
Baur et al. 1993	Molluscs (1)		6.2 m		Natal?
In Baur et al. 1993	Molluscs (1)		10 m		Natal?
Cowie 1984	Molluscs (1)	3 m			Natal?
Riecken et al. 1996	Insects (1)	132.5 m			8 Days
Anon	Insects (2)	30-300 m			
Duelli et al. 1990	Spiders (?) Insects (?)	150 m 150 m			
Jensen et al. 1989	Insects (1)	190 m			
Smith et al. 1996	Ticks (1)	9.7 km			Via Birds Minimum
Stafford 1992	Ticks (1)	2.1 m			Larva Unaided
Carroll et al. 1996	Ticks (1)	15 m	2.3 m		Larva

		8 m	4.5 m		Adult

The Pilot Model

As ecosystems change, the ability to model their future states and the potential dispersal of plants and animals across them provides a valuable tool for devising and assessing adaptation strategies and potential management practices.

This project provided the means for developing such a model in the *Altered Ecosystem Generalized Incremental Simulation (AEGIS)*, which generalizes a simulation of the extant ecosystem from detailed digital descriptor data and alters this in annual increments to represent a future ecosystem. The potential of plant and animal taxa to disperse on the landscape is modeled in this simulated ecosystem by correlating organism parameters with ecosystem type.

Thus, in the context of this project, the development of this model is concerned with two aspects: modeling the state of the future ecosystem, and modeling the dispersal potential of taxa within it. The purpose of this pilot version of AEGIS is primarily to assess and prove the methodology developed for modeling terrestrial functions in the prairie ecozone of Saskatchewan under conditions imposed by changing climate. As such, the pilot model focuses on two study watersheds in the southern portion of the prairie ecozone, identified as the Moose Jaw River and Frenchman River (defined below in the Extant Landscape Component). However, the approach developed here may be extended to any ecosystem that can be digitally simulated. Imposed conditions, while defined in this model by climate, may be otherwise provided by any parameters that can be adequately described (such as land use or economics).

GENERAL METHODOLOGY

The development of the model essentially consisted in constructing a digital representation of the southern Saskatchewan ecosystem in a GIS environment, and describing the extant landscape and climate in terms relating to dynamic characteristics of the ecosystem and the persistence and movement of biotic populations within it. Algorithms were then applied to define the altered climate and the resultant altered landscape for a future time period. The subject taxa, similarly described in terms of ability to inhabit and disperse within an ecosystem, were correlated with this modified ecosystem and projected onto the future landscape, modeling potential species dispersal.

Since a large number of potential variables are involved in the establishment and persistence of a particular population within a given ecosystem, an examination of the detailed interactions of organisms with their environment is beyond the scope of this modeling exercise. An analogue approach was therefore taken in modeling *potential* taxa dispersal, in which ecological conditions subject to alteration by change in climate were modified in accordance with a projected future climate, and species populations assumed to disperse under this altered regime as under previously similar conditions. Thus, it is an organism's relationship to a defined ecosystem (e.g. that a particular bird inhabits native grassland or parkland) that were considered for modeling purposes, rather than the complexity of variables that define this relationship; it is at this level that taxa dispersal was studied in the model.

Modeling taxa dispersal on a future landscape therefore entailed modeling the future subject ecosystem. An ecosystem may be considered as consisting of relatively static and dynamic processes. Those not subject to short-term change (i.e. not subject to qualitative change within the proposed model time frame) were taken to be static, including such things as soils and landform. For modeling purposes, static functions were not considered within the framework of the modeling process. Dynamic functions are those subject to change within the time frame of the model period, consisting mainly of the interaction of temperature and water within an ecosystem and its resultant biotic structure. These functions were addressed in describing future conditions. Since an ecosystem is a product of climate, modeling a future ecosystem became a process of modeling the *effects* of the formative climate.

The model was therefore built up from a series of model components, comprising: Extant Landscape, Extant Climate, Altered Climate, Altered Landscape, Taxa Definitions, and Taxa Dispersal. The extant landscape and extant climate together model the present, or baseline, ecosystem. Applying climate change factors, derived from the mean of a selection of global climate change models, to the extant climate describes a plausible altered climate for a future model period. Applying the altered climate to the extant landscape, in turn, yields a future altered landscape and ecosystem. Applying the subject taxa definitions to this future ecosystem produces a plausible model of potential taxa dispersal on the future landscape.

Numerous data sources may exist describing a particular condition of a given ecosystem; such data sets, collected at different times and in different ways, may not be in agreement. Similarly, a particular data set may be applied and manipulated in various ways. Ecosystem descriptor data were therefore considered in a relative context in the model, i.e. data sets were considered primarily as proxy indicators for the conditions being described, rather than the specific data values contained. The consideration was to ensure that the subject condition was described by the data in a manner such that the condition=s ramifications within the ecosystem were adequately defined for modeling purposes. As long as this is achieved, actual data values are not in themselves of central significance to most aspects of the modeling process. For example, in describing an >arid= ecosystem, conditions such as precipitation and potential evapotranspiration were considered. The data values describing these conditions, however, are significant only to the degree that they uniquely describe the conditions defining aridity (whether this is accomplished by a water balance value of -285 mm or -430 mm is immaterial to the modeling process as long as the definition is unique). Thus, the approach taken wherever possible was to acquire data describing conditions from existing ecosystems, and apply these as descriptors to represent comparable conditions in a potential future scenario.

The spatial resolution determined for the operation of the model was a one-half mile square grid cell, as defined by the Dominion Land Survey quarter-section grid. This was considered an appropriate spatial framework given the scope of the project, available computing power, and particularly, the structure and resolution of available descriptor data. Aspects of ecosystems, such as vegetation that vary at a finer resolution than the quarter-section grid cell were extrapolated to the grid cell level. Aspects such as climate that vary at a much coarser resolution were represented at the grid cell level through GIS interpolation processes. All ecosystem descriptors were therefore defined at this spatial resolution through linkage to the quarter-section grid within the GIS.

An *a priori* assumption was made that conditions effective for a species population to persist or transit either existed or did not exist at the defined quarter-section grid cell level. Since potential taxa dispersal was being modeled, the consideration was whether ecological conditions capable of sustaining populations or serving as transit corridors were either present or absent. Further quantification of these conditions was not of concern in terms of assessing dispersal capability.

The temporal resolution of the model was annual, cycling through the ecosystem alterations and taxa dispersal processes and incrementing the model at each annual iteration. Dynamic functions of the ecosystem varying at a finer resolution than annual were extrapolated to the annual resolution. Annual increment results were internally retained within the system and can be recalled for any iteration in graphic or statistical form. The time frame selected for the operation of the pilot version of the model is nominally 50 years, extending from the present to the year 2050, with conditions for 2050 nominally represented by the intermediate 30 year future scenario as defined by the Intergovernmental Panel on Climate Change (IPCC) and the Canadian Centre for Climate Modeling and Analysis (CCCMA).

EXTANT LANDSCAPE COMPONENT

The Extant Landscape component models the existing landscape, representing the topographic functions of the baseline ecosystem and providing spatial parameters for the modeling processes. Topographic descriptors were represented by digital data sets defining the aspects of the landscape subject to change by imposed climate conditions and pertaining to the modeling potential dispersal of selected taxa. Additional data sets supplied the parameters that defined and coordinated the model working space.

< *Spatial Coordinate Framework*

The quarter-section cadastral represents the one-half mile square (160 acre) land parcel survey grid as defined by the Dominion Land Survey System, and was supplied from the digital Provincial Township Fabric database. The quarter-section data set serves as the geometric framework and coordinate descriptor, spatially defining the model and coordinating all data sets to a common quarter-section grid, thus defining the working resolution to a one-half mile square grid cell. In terms of modeling the baseline and future ecosystems and potential taxa dispersal, all data were represented and processed at this one-half mile grid cell resolution within the GIS.

< *Spatial Delimiter*

The watersheds constitute landscape definitions, as classified by us, at a scale below that of the ecoregion, and consist of watersheds defined by the PFRA Gross Watershed database amalgamated into landscape units according to various characteristics (see Watershed Classification). The Moose Jaw River and Frenchman River watersheds, located respectively in the south-central and extreme southwest of the prairie ecozone, define the two study areas selected for the pilot model (Fig. 4).

< *Visual Reference*

The National Topographic System 1:50,000 scale digital map sheet neat line grid was incorporated as the primary visual reference for mapped model data. Additional visual reference is provided by selected major features from the National Topographic System 1:50,000 scale digital map sheet drainage theme and selected urban centres from the 1:1,000,000 scale map sheet communities theme.

< *Vegetative Regime*

The landscape descriptor for the pilot model consists of the extant vegetative regime, represented by acreage values per quarter-section for selected classification fields from the PFRA Land Cover database, defining baseline vegetative conditions such as woodland, grassland and cropland. Interpreted from satellite data, these classes serve as a proxy for average vegetative conditions. The vegetative classes were drawn from the data set directly as >Woodland=, and indirectly by amalgamating the grassland and shrub fields to obtain >Grassland=, and the cultivation and forage fields to obtain >Cropland=. Grassland is characterized by long-term perennial vegetation other than trees and wetlands and is utilized in the model as a further proxy for native prairie. Cropland characterizes regular cultivation. Woodland characterizes significant tree content. Two additional classes, >Dry Cropland= and >Arid=, further defined under the Altered Landscape Component, were created by the modifying algorithms in defining the vegetative regime for future time periods. The remaining fields of the source data set were assigned to >Other= or >No Data= as appropriate. Mapped model output for the extant vegetative regime is similar to the altered vegetative regime, described below under the Altered Landscape Component.

EXTANT CLIMATE COMPONENT

The Extant Climate component models the existing climate, representing the climatology of the baseline ecosystem. Climate descriptors are represented by digital data sets defining climate aspects necessary for modeling the potential future landscape and potential future dispersal of selected taxa.

< *Temperature*

Temperature conditions for the extant climate are represented by the temperature theme of the Environment Canada Gridded Prairie Climate Normals database, a 30 year baseline climatology describing the 1961 to 1990 time frame in a 50 km grid. A 30 year mean annual temperature value, expressed as the annual mean of the 30 year monthly means in ^{o}C, was drawn from the source data for each applicable global climate model grid cell. These values, interpolated from the global climate model grid cells through a triangulated irregular network procedure to the quarter-section grid cells, define baseline mean annual temperature for the ecosystem.

< *Precipitation*

Precipitation conditions for the extant climate are represented by the precipitation theme of the Environment Canada Gridded Prairie Climate Normals database, as described above. A 30 year mean annual precipitation value, expressed as the annual mean of the 30 year monthly means in mm, was drawn from the source data for each applicable global climate model grid cell. These values, interpolated from the global climate model grid cells through a triangulated irregular network procedure to the quarter-section grid cells, define baseline mean annual precipitation for the ecosystem.

< *Potential Evapotranspiration*

Potential evapotranspiration conditions for the extant climate are represented by the potential evapotranspiration field of the Canadian Global Climate Model baseline data, a 30 year climatology describing the 1961 to 1990 time frame in a

3.75E longitude by 3.71E latitude grid. A 30 year mean annual potential evapotranspiration value, expressed as the daily mean in mm for the 30 year period, was drawn from the data set for each applicable global climate model grid cell. These values, interpolated from the global climate model grid cells through a triangulated irregular network procedure to the quarter-section grid cells and extrapolated to annual, define baseline mean annual potential evapotranspiration for the ecosystem.

ALTERED CLIMATE COMPONENT

The Altered Climate component models the future climate, representing the climatology of the future ecosystem. Future climate descriptors are represented by applying climate change factors to the baseline extant climate descriptors. These change factors were derived from four internationally recognized global climate change models, the Canadian CGCM1, the British HadCM2, the Australian CSIROMk2b, and the Japanese CCSR98, functioning on similar spatial resolutions and providing climate change experiments combining both greenhouse gases and sulphate aerosols. Gas/aerosol experiment results were utilized for the pilot model since these were thought to be more realistic.

Since the pilot model has been designed to function through a 50 year time frame defined as the period extending from the present to 2050, the year 2050 was represented by the intermediate 30 year future climatology projected by the global climate models. A simple linear interpolation, dividing the climate change factors into 50 increments, applies this time frame to the pilot model as an annual temporal resolution. Modeling realistic conditions for taxa dispersal within the ecosystem (i.e. providing for a >stepped= pathway to dispersal) was accommodated by running the dispersal model through 50 iterations, altering the ecosystem, applying the taxa, and modeling the dispersal at each iteration.

< *Altered Temperature*

Altered temperature conditions for the future climate are represented by applying a change factor to the extant temperature descriptor. The change factor (Δtemp) was derived from a simple mean of the temperature change fields of the four global climate models, where the change values (^{o}C) from each climate model were interpolated individually to the quarter-section grid cell level of the pilot model using a linear procedure in a triangulated irregular network. The four values were then averaged at the quarter-section level, producing a single mean change value for each dispersal model grid cell. A simple linear interpolation was deemed sufficient for the pilot model due to the extreme coarseness of the global climate model data. Interpolation to the annual temporal resolution of the pilot model was accommodated by dividing the change values into 50 increments, deriving Δtemp in ^{o}C so that in modeling for any year *n* of the pilot model, $temp_0 = temp_0 + (((\Delta temp)\ 0.02)\ n)$, where >temp= represents temperature and >0' represents the baseline ecosystem.

< *Altered Precipitation*

Altered precipitation conditions for the future climate were represented by applying a change factor to the extant precipitation descriptor. The change factor (Δprec) was derived from a simple mean of the precipitation change fields of the four global climate models, where the change values (as % of baseline values) from each climate model were interpolated to the quarter-section grid cell level as above.

Interpolation to the annual temporal resolution of the pilot model was accommodated by dividing the change values into 50 increments, deriving Δprec in % so that in modeling for any year *n* of the pilot model, $prec_0 = prec_0 + ((((\Delta prec / 100)\, prec_0)\, 0.02)\, n)$, where >prec= represents precipitation and >0' represents the baseline ecosystem.

< *Altered Potential Evapotranspiration*

Altered potential evapotranspiration conditions were represented by applying a change factor to the extant potential evapotranspiration descriptor. The change factor (Δpevt), available from the Canadian Global Climate Model only, was derived from the potential evapotranspiration change field (as % of baseline values), and interpolated to the quarter-section grid cell level as above. Interpolation to the annual temporal resolution of the pilot model was accommodated by dividing the change values into 50 increments, deriving Δpevt in % so that in modeling for any year *n* of the pilot model, $pevt_0 = pevt_0 + ((((\Delta pevt / 100)\, pevt_0)\, 0.02)\, n)$, where >pevt= represents potential evapotranspiration and >0' represents the baseline ecosystem.

ALTERED LANDSCAPE COMPONENT

The Altered Landscape component models the potential future landscape, representing the topographic structure and dynamics of the future ecosystem. Applying the Altered Climate component to the Extant Landscape component produces the potential future altered landscape.

Since the pilot model functions through a nominal 50 year time frame as described above in the Altered Climate component, modeling realistic conditions for taxa dispersal within the ecosystem was accommodated by running the model through 50 iterations, altering the ecosystem, applying the taxa, and modeling dispersal at each iteration. For purposes of the pilot model, baseline landscape functions subject to change under climatic influence consist only of the vegetative regime.

< *Altered Vegetative Regime*

The altered vegetative regime for the future landscape is described by five classes: Woodland, Grassland, Cropland, Dry Cropland, and Arid. The vegetative regime was considered solely as a product of climate for the purposes of the model. The baseline vegetative regime, as represented by the *W*oodland, Grassland, and Cropland vegetative classes (defined above in the Extant Landscape component), was therefore subject to alteration through climatic influence. In altering the vegetative regime an assumption has been made that the driest region of southern Saskatchewan is presently on the cusp of aridity, and that a net reduction in available water within the ecosystem will drive this region to arid conditions. This potential shift toward aridity necessitated provision for two additional derived classes, Dry Cropland and Arid. Arid, indicating trend towards desertification, is characterized by vegetative conditions without precedent in terms of dryness (i.e. negative water balance) in the Saskatchewan prairie ecozone, typified by parched soils subject to drifting, and hosting sparse, if any, vegetation with tolerance to extreme drought. Dry Cropland indicates a transition phase as Cropland moves to Arid, and is characterized by vegetative conditions of borderline aridity on soils presently or previously under cultivation.

In terms of modeling climatic influence on an ecosystem, recent research identifies water balance as the definitive formative factor for the vegetative regime, described by the formula: mean annual precipitation minus mean annual potential evapotranspiration (prec - pevt; Hogg 1994, Hogg et al. 1995, 1997). Using this standard, parameters were determined for modeling the altered vegetative regime for the future landscape from the relationship between water balance and the vegetative regime of the extant landscape. From this analysis, according to the climatological descriptors utilized for the two study areas, vegetative transitions were defined for each grid cell for any year *n* of the pilot model at the following water balance thresholds:

$prec_n - pevt_n > -255$mm; baseline vegetative status remains unchanged
$prec_n - pevt_n < -255$mm; Woodland converts to Grassland
$prec_n - pevt_n < -275$mm; Cropland converts to Dry Cropland
$prec_n - pevt_n < -280$mm; Dry Cropland converts to Arid
$prec_n - pevt_n < -285$mm; Grassland converts to Arid

These transitions were considered ecologically valid for the vegetative regime under conditions of increasing water deficit. Latent grasses within Woodland would permit Woodland to shift to Grassland (as witnessed in woodland die-off in the Parkland Ecoregion during the droughts of the early 1960s and late 1980s). Native grassland would not re-establish so readily on Cropland since no basis for native grasses remains. Cropland therefore deteriorates towards the non-productive condition defined as Dry Cropland (as seen across the prairies in the 1930s). *Dry Cropland* can shift to Arid earlier than Grassland under the same water balance regime (also witnessed in the 1930s) due to the higher tolerance to drought of native prairie vegetation. The threshold for aridity was established at a water balance value below the lowest extant value recorded for the driest region of the prairie ecozone; beyond this point, all vegetative classes shift to arid conditions.

While each vegetative class is individually accessed within the model by the vegetative alteration and taxa dispersal functions, it is not possible to visually represent all classes for each grid cell at a quarter-section resolution. Mapped model output therefore shows only a single class where a class represents at least 90% of the grid cell. Otherwise, the two largest classes are shown. Thus, output graphics for the altered vegetative regime depict the vegetative classes as: Woodland, Grassland, Cropland, Grassland/Cropland, Woodland/Cropland, Woodland/Grassland, Dry Cropland, Dry Cropland/Grassland, and Arid.

TAXA DEFINITION COMPONENT

The Taxa Definition component describes the subject taxa in terms of its ability to inhabit and disperse across the landscape, and consists of parameters specifying habitat requirements, annual dispersal capability, and barriers to dispersal.

For the pilot version of the model, these parameters comprised: vegetative requirements (as supplied by the vegetative regime and altered vegetative regime descriptors), annual dispersal distance (dispersal distance per annual increment and model iteration), and dispersal barriers that can be addressed by the above landscape descriptor data. Further parameter refinements for the model could stipulate quantity per grid cell as either present or full for vegetative requirements.

TAXA DISPERSAL COMPONENT

The Taxa Dispersal component models potential dispersal of the subject taxa on the future altered landscape. Taxa were correlated with the functions of the modeled future ecosystem that relate to taxa population dispersal, producing potential dispersal ranges from selected start points for any year *n* of the modeling process.

As noted in the Altered Climate and Altered Landscape sections, the pilot version of the model operates through a nominal 50 year time frame at an annual temporal resolution, applying the alteration processes through 50 iterations. This procedure provides for modeling change in the ecosystem and potential taxa dispersal in annual increments. This is necessary because the majority of organisms disperse over a specific distance on an annual basis, and because ecosystem conditions affecting dispersal in earlier stages of the modeling process may become non-conducive in subsequent increments, yet potentially facilitate dispersal in the interim.

The algorithms driving the dispersal functions compare the taxa parameters with the altered ecosystem conditions grid cell by grid cell, commencing at the selected start point(s) and searching outward by annual increments. The dispersal distance parameter defines the extent of the search at each model iteration, describing a circular search zone (with dispersal distance as radius) centered successively on each grid cell identified as supporting dispersal at the immediately previous iteration. Thus, for any given increment, all grid cells encountered by this progressively positioned search zone that possess conditions fulfilling the taxa parameters are identified as supporting taxa dispersal. Hence all potential dispersal corridors are detected, with the dispersal distance defining links to non-adjacent supportive grid cells. Since the objective was to study *maximum* dispersal potential, stochasticity was not factored into the model methodology.

So for any year (annual increment) *n* of the taxa dispersal modeling process, the subject ecosystem (climate and landscape) is modified by the Altered Climate and Altered Landscape components, and the dispersal distance search zone is positioned successively on each supportive grid cell identified at *n-1,* the immediately previous increment (the start point grid cell(s) constitute(s) *n-1* for the first increment). By this process, each grid cell supporting dispersal at increment *n-1* serves as a nucleus for the dispersal distance search zone at increment *n*, retesting all previously supportive cells at each successive iteration for conditions becoming non-supportive to dispersal or continued habitation. Grid cells encountered by the search zone that continue to meet the taxa parameters constitute the potential range of dispersal for year *n* of the model. Successive annual dispersal ranges were recorded either as separate channels of a file or as separate files, and can be recalled individually as either text or graphics for analysis or presentation purposes. Mapped model output identifies the dispersal ranges as overlays on the landscape at the quarter-section grid cell resolution.

Results and Discussion

Baseline (year 2000) vegetative regime, mean annual temperature, mean annual precipitation, and mean annual potential evapotranspiration are shown for the two study watersheds in Figs. 5 to 8 respectively. For illustrative purposes, we only show the 50 year time step for subsequent changes. Mean annual temperature, mean annual precipitation, mean annual potential evapotranspiration, and the calculated water balance for the two watersheds in 2050 are shown in Figs. 9 to 13 respectively. The resultant vegetation regime for the two watersheds in 2050 is shown in Fig. 13, and the dispersal of a hypothetical taxon population over the 50 year cycle is shown in Fig. 14. For this population, we assumed an annual dispersal capability of one kilometer per year and preferred habitat of >Grassland=. Their initial starting points were randomly selected.

Vegetative changes occur within the two watersheds over the 50 year modeling period, but less markedly so in the Moose Jaw watershed (Table 2). The most striking change in the Frenchman watershed is a dramatic increase in the vegetation class >Arid=, centered around the town of Val Marie (Fig. 13). Indeed, by the year 2050, almost 24% of this watershed is classified as >Arid=. Changes in the Moose Jaw watershed are more subtle, but there are shifts towards drier vegetation classes. Of particular interest are two zones of >Dry Cropland= and >Dry Cropland/Grassland= which appear to the west of Regina and at the edge of the Missouri Coteau south of Moose Jaw (Fig. 13).

Table 2. Percentage Change in Vegetative Classes for the Frenchman and Moose Jaw Watersheds Between 2000 and 2050

Vegetation Class	French 2000	French 2050	Net Change	MJ 2000	MJ 2050	Net Change
Crop	22.4	13.6	- 8.8	59.9	57.9	- 2.0
Grass	56.9	47.0	- 9.9	11.1	12.0	0.9
Wood	< 0.1	< 0.1	0.0	0.0	0.0	0.0
Crop/Grass	15.5	9.6	- 5.9	26.1	25.7	- 0.4
Crop/Wood	~ 0.1	< 0.1	- 0.1	0.8	0.3	- 0.5
Grass/Wood	4.9	1.3	- 3.6	1.0	0.1	- 0.9
Other	~ 0.1	~ 0.1	0.0	1.0	1.0	0.0
No Data	0.0	0.0	0.0	0.2	0.2	0.0
Dry Crop/Grass	0.0	1.3	1.3	0.0	0.8	0.8
Dry Crop	0.0	3.1	3.1	0.0	2.0	2.0
Arid	0.0	23.8	23.8	0.0	0.0	0.0

Clearly, these ecosystem shifts, particularly in the Frenchman watershed, will signal significant changes in the distribution and abundance of many prairie species, and some interesting challenges for the human communities of the area.

These differences between the two watersheds also have quite different consequences for a hypothetical species population attempting to disperse across them (Fig. 14). The starting point of the population in the Frenchman watershed happened to coincide with that of the growing area of aridity. As a result, the population barely keeps ahead of the ecosystem change over the 50 year time period, and is split into two disjunct populations. Its initial population is eliminated in the process, as is a large proportion of its population on newly-settled areas. This hypothetical species population does better on the Moose Jaw watershed (Fig. 14). However, the role that habitat loss and fragmentation plays in the ability of species to move is clearly evident on this watershed; dispersal to the west and south is significant but is much less so to the east and north. The value of relatively thin habitat corridors for the movement of species is also evident on this watershed.

Future Work

Now that the model is running successfully on two pilot watersheds, the next step is extend its application to the entire prairie ecozone of southern Saskatchewan. Having done this, the model could then be used to identify critical habitat parcels that are predicted to facilitate the movement of species across the landscape. It could also be used to simulate the fate of the several hundred rare plants whose locations have been identified in the province, which in turn would lead to proposed management actions. However, AEGIS was designed and built as a general ecosystem model hence it has much more to offer. For example, digital aquatic ecosystems databases are becoming more available. We are interested in incorporating these and other data layers into the model so that predictions of the impact of climate change on these systems can be generated. In addition, AEGIS can play a role in land use planning with respect to climate change. For example, changes in agriculture are clearly going to occur in southern Saskatchewan. Future ecosystem scenarios can be generated to better inform these decisions. In connection with this, there are discussions underway to diversify agriculture along the forest fringe through agroforestry initiatives. Understanding how forested ecosystems might change over the next few decades can again support these adaptation measures.

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