The Potential for Land Degradation Under Climate Change in the Vicinity of Six Rural Communities in Saskatchewan

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ABSTRACT. The landscape of southern Saskatchewan is drought prone and dominated by agriculture. Certain landscapes are more sensitive to degradation. Given the potential impact of climate change on the landscapes and their productivity, a regional scale investigation was undertaken using three global climate models (GCMs) and two geographic information system (GIS) overlay methods to examine the sensitivity of the landscapes surrounding the six rural communities of Balcarres, Carlyle, Craik, Eastend, Naicam and Willow Bunch for the periods of 1961–91 and for the 2050s. Regardless of the method used, the most sensitive landscapes are land under cultivation. However, the degree of sensitivity of those landscapes to climate change depends on the weighting of factors and the global climate model (GCM). Of the three GCMs used to predict sensitivity for the 2050s, CGCM1 and CGCM2 generally showed the largest increases while HadCM3 generally forecasted a decrease. Thus, the landscape sensitivity of the six study sites resulting from climate change is predicted to increase according to two of the three GCMs, resulting in the expansion of the land area at risk of land degradation.

SOMMAIRE. Le paysage du sud de la Saskatchewan est exposé à la sécheresse et dominé par l'agriculture. Certains paysages sont plus sensibles à la dégradation. Étant donné l'impact potentiel du changement climatique sur les paysages et leur productivité, une investigation à l'échelle régionale a été entreprise à l'aide de trois modèles climatiques globaux (MCG) et de deux méthodes à recouvrement à base de systèmes d'information à référence spatiale (SIG) afin d'examiner la sensibilité des paysages autour des six communautés rurales de Balcarres, Carlyle, Craik, Eastend, Naicam et Willow Bunch pour 1961–91 ainsi que pour les années 2050. Peu importe la méthode utilisée, les paysages les plus sensibles sont ceux des cultures. Cependant, leur degré de sensibilité au changement climatique dépend du rapport de pondération et du modèle climatique global (MCG). Des trois MCG utilisés pour prédire la sensibilité des années 2050, MCG1 et MCG2 affichaient en général les augmentations les plus importantes, tandis que MCG3 prévoyait une diminution. Selon deux des MCG, la sensibilité des six sites d'étude au changement climatique est donc censée augmenter, ce qui amènera une expansion des terres menacées de dégradation.

Introduction

The landscape of southern Saskatchewan is dominated by agricultural production and periodic drought, raising the potential for soil degradation (Sauchyn et al., 2005). Severe drought is forecast to occur with increasing frequency under global warming (Kharin and Zwiers, 2000). Identification of sensitive landscapes (Allison and Thomas, 1993) on a regional scale based on present-day and future climates supports the implementation of land management practices to reduce the risk of soil degradation. The original prairie ecosystems have been modified to such an extent that their vulnerability to climate change influences the sustainability of rural prairie communities (Gauthier and Henry, 1989).

One of the objectives of the southern Saskatchewan social cohesion project was to assess the relative impacts of climatic variability and change on the viability of rural communities. The study described here addressed this objective by determining: (1) those landscapes that may be sensitive or prone to landscape degradation given the present-day climatic, edaphic and biophysical conditions; and (2) how the sensitivity of these landscapes may be affected by climate change.

Soil landscapes respond to rain, wind and runoff above certain thresholds and according to the degree of resistance to the specific disturbance. Landscape change in response to climate change is the result of the complex interplay between hydroclimatic events and climatically-driven geomorphic processes (Eybergen and Immeson, 1989). A new climate regime may cause changes in the rate of geomorphic processes and induce transient behaviour to the landscape system (Lee et al., 1999). Changes in the climatic parameters can also indirectly impact a landscape by reducing resistance within a landscape, making it more susceptible to degradation forces. Because they are highly variable, there tend to be parts of soil landscapes that are more sensitive or less resistant. This produces a patchwork of sensitive and less-sensitive areas depending on the soil and topographic properties and the processes acting on the landscape. Various physical and cultural factors determine the exposure of soil to degradation. The concept of desertification supports a broad assessment of the degradation of drylands and emphasizes the relationships between geomorphic, socio-economic, and climatic processes and the landscape (Grunblatt et al., 1992). Desertification is defined as: "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variation and human activities" (UNCCD, 1994: 4).

By this definition the subhumid southern Prairies are at risk of desertification; they also are exposed to climate change (Sauchyn et al., 2005). The global increase in average surface temperature of about 0.6°C during the 20th century (IPCC, 2001) was mirrored in the Prairies, which had the largest increase for all of Canada. From 1900 to 1998, the annual mean daily maximum temperature increased about 1.5°C, with warming in spring and summer representing the greatest increase in the annual temperature (Zhang et al., 2000). About 40% of the Prairie provinces' economic activity consists of primary agricultural production, with a large proportion of secondary economic activity in support of the agricultural sector (Meyer, 1997). Any change to the Prairie climate that might increase its aridity or variability could have serious ecological and financial consequences for the landscape of the southern Prairies.

Modeling Landscape Sensitivity and Climate Change

The six rural communities of Balcarres, Carlyle, Craik, Eastend, Naicam and Willow Bunch were the focus of the southern Saskatchewan social cohesion project. To assess the sensitivity of the landscapes associated with these communities, the boundaries of investigation were expanded beyond the individual town sites to the surrounding Rural Municipalities (Table 1). The six study sites are plotted in Figure 1with the CCGM1 grid cells showing forecasted change in annual temperature for the 2050s.

Digital topographic and soil maps for southern Saskatchewan are relatively coarse at scales of 1:50 000 and 1:100 000 (Table 2), corresponding to a resolution of 25 to 50

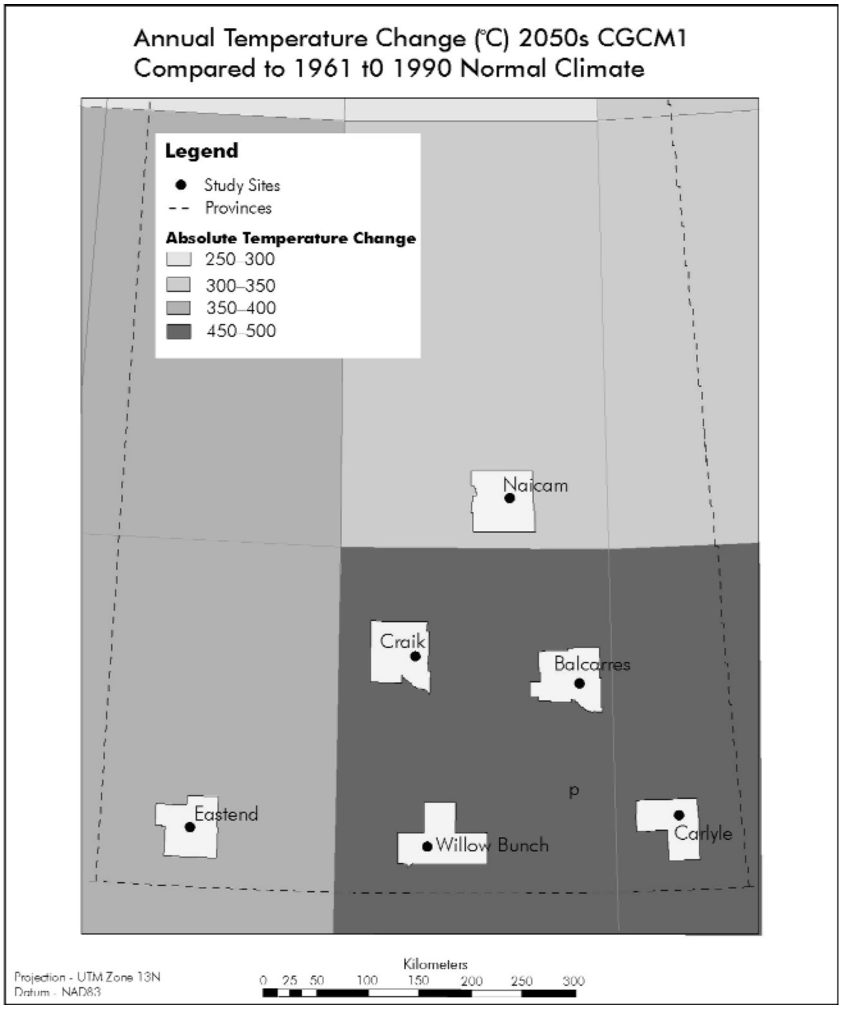


Figure 1. The six study sites plotted with the CCGM1 grid cells showing forecasted change in annual temperature for the 2050s. Four communities are in the southeastern cell; Eastend falls in the southwestern cell and Naicam falls in the east-central cell (see Table 3).

metres. The scenarios of future climate have the coarse temporal and spatial scales (months and hundreds of kilometres) of GCMs. This scale necessitates the use of relatively simple models to simulate the sensitivity of landscapes and to compare present-day and future sensitivity. Because individual processes are not modeled at this scale, the evaluation of degradation or desertification, and the various processes and factors

Table 1. Study Sites and Associated Rural Municipalities

Balcarres	Carlyle	Craik	Eastend	Naicam	Willow Bunch
North Qu'Appelle, No. 18	Moose Creek, No. 33	Craik, No. 222	White Valley, No. 49	Pleasantdale, No. 39	Bengough, No. 40
Abernethy, No. 186	Moose Mountain, No. 63	Huron, No. 223	Arlington, No. 79	Spalding, No. 368	Willow Bunch, No. 42
Tullymet, No. 216	Brock, No. 64	Arm River, No. 252		St. Peter, No. 369	Excel, No. 71
Lipton, No. 217		Willner, No. 253		Lake Lenore, No. 399	

Table 2. Digital Data used in the Investigation

Digital Information	Scale*	Source	Region or Map Sheet
Topographic	1: 50 000	ISC	NTS Map Sheets
Soil	1: 100 000	SPARC	RM Soil Surveys
Landcover	1: 1 000 000	PFRA	Prairie Provinces (Agricultural Region)
Climate	50 km	EC	Normals (1961 to 1990) on a 50 km grid and selected meteorological stations
GCMs	3.75° × 3.75° latitude; 2.5° × 3.75° longitude	CCIS	Global

*Scale or resolution at which the data were captured.

Abbreviations: Information Services Corporation of Saskatchewan (ISC), Semiarid Prairie Agricultural Research Centre (SPARC), Prairie Farm Rehabilitation Administration (PFRA), Rural Municipalities (RM), Canadian Climate Impacts Scenarios (CCIS), National Topographic Series (NTS), Environment Canada (EC)

Table 3. Temperature and precipitation change projected by CGCM2 (warm-wet), HadCM2 (wet-cool), scenario and CGCM1 (dry-warm) for the 2050s and the IS92a emission scenario (ensemble-mean simulations with aerosol forcing) and for each of the four cells encompassing southern Saskatchewan.

Experiment	Temperature Change (°C)	Precipitation Change (Percent)
	Southeastern Saskatchewan	
CGCM1	4.2	1
CGCM2	4.4	5
HADCM2 1	2	15
	Southwestern Saskatchewan	
CGCM1	3.6	2
CGCM2	3.9	7
HADCM2 1	2	18
	West-central Saskatchewan	
CGCM1	3.7	6
CGCM2	3.8	5
HADCM2 1	2.1	11
	East-central Saskatchewan	
CGCM1	3	6
CGCM2	3.1	8
HADCM2 1	2.1	8

Source: Canadian Climate Impact Scenarios Project – www.cics.uvic.ca/scenarios. Four communities are in the southeastern cell; Eastend falls in the southwestern cell and Naicam falls in the east-central cell (see Figure 1).

involved, usually requires an assessment of risk (FAO/UNEP, 1983; UNEP, 1992; Grunblatt et al., 1992; Basso et al., 2000).

The digital geographic data include (Table 2) National Topographic System (NTS) maps sheets, soil polygons at the series level of the Canadian System of Soil

Classification, the digital Generalized Landcover for the agricultural region of Canadian Prairies, monthly precipitation and temperature normals (1961 to 1990) on a 50 km grid, and GCM outputs. All data sets were transformed to a common resolution of 50-metres. The GCMs were the first and second version of the Canadian Global Coupled Model (CGCM1, CGCM2) and the Hadley Centre's Second Generation Coupled Ocean-Atmosphere GCM (HadCM2). These GCMs were chosen to obtain a range of possible future climates as recommended by the Intergovernmental Panel on Climate Change (IPCC-TGCIA 1999), with CGCM2 representing a warm-wet scenario, HadCM2 the wettest and coolest scenario and CGCM1 the driest-warm scenario (Table 3). Outputs from the GCMs were obtained from the Canadian Climate Impact Scenarios Project web site (http://www.cics.uvic.ca/scenarios/) for the 2050s (2040–69). All three models were ensemble-mean simulations with aerosol forcing using the IS92a emission scenario.

Factor Weighting and Spatial Overlay

Our approach to the spatial modeling of soil landscape sensitivity in the vicinity of the six rural communities is described in detail by Kennedy (2004). It is based on factor weighting and spatial overlay, semi-quantitative methods used in various disciplines (e.g., Jiang and Eastman, 2000; Wilkie et al., 2001; Basnet et al., 2001) to incorporate uncertainty caused by a lack of knowledge about the true nature of the structures or processes and the final result or outcome. Given an objective or question, this method recognizes that there are a series of causal factors that have the greatest influence on the result (Basso et al., 2000). These factors are identified, standardized, weighted and then combined to produce a range of possible results from best- to worst-case scenarios. Therefore, the method, while not predictive in the sense of cause and effect, produces results that indicate spatially those combinations of causative factors that produce the highest risk or greatest suitability depending on the given question or objective.

While used primarily in a GIS environment in a decision support role, the factor weighting and spatial overlay method has been applied widely to land resource evaluation and risk analysis (Basnet et al., 2001; Wilkie et al., 2001). It also has been used to investigate the risk or likelihood of desertification at coarse spatial scales (FAO/UNEP, 1983; Grunblatt et al., 1992; Basso et al., 2000). Relevant factors normally are identified from "expert knowledge" which requires an *a priori* knowledge of the factors or indicators most relevant to the objective and/or salient to the system. Given data limitations, only three aspects of desertification risk are considered here: sensitivity of the landscape to aridity and the processes of rainfall erosion and wind erosion. Landscape sensitivity was determined by computing indices of aridity, rainfall erosivity and wind erosion for the normal period (1961 to 1990) and for the 2050s (2040–69) according to functions listed in Table 4. Climate variables for the 2050s were evaluated using data for 1961 to 1990 and climate change fields: absolute difference in °C from the normal period for monthly temperature; percent change for precipitation and wind speed.

The Aridity Index (AI), a numerical expression of dryness, is the ratio of annual precipitation to annual potential evapotranspiration. Potential evapotranspiration was calculated using the Thornthwaite formula (Thornthwaite and Mather, 1957). It requires only monthly temperature and day length data. An AI of less than 1.0 represents an annual moisture deficit. Thus lower AI values indicate higher aridity and greater susceptibility (sensitivity) to degradation. The classification of drylands is based on AI values. Semiarid

Table 4. Computation of Landscape Sensitivity Factors

Equation	Terms
Aridity Index AI = (P / PET).	AI – Aridity Index P = annual precipitation PET = annual potential evapotranspiration
Fournier Index (modified for the months above 0 °C) $C = \sum_{i=1}^{7 or 8} \frac{p_i^{2}}{P}$	C = Climate Index p_i = Rainfall in month i (mm) P = Annual Rainfall (mm)
Wind Erosion Climatic Factor $C = 386(u_z)^3 / I^2$ **Precipitation Effectiveness Index** $I = \sum_{i=1}^{12} 115((P_i / 25.4) / 1.8T_i + 22))^{1.11}$	C = Wind Erosion Climatic Factor U_z = the mean annual wind speed (m/s) I = the precipitation effectiveness index P = the monthly precipitation (mm) T = the monthly mean temperature (°C)
Linear Standardization $x_i = (R_i - R_{\min}) / (R_{\max} - R_{\min}) \times 255$	x = Standardized Score R = Raw score

and subhumid landscapes (AI = 0.05–0.65) are at risk of desertification (UNCCD, 1994).

The modified Fournier index is a climate index of rainfall erosivity requiring minimal data (Arnoldus, 1980). For the normal period, the modified Fournier index was calculated using data from April to October when mean monthly temperatures generally are above 0° C and precipitation is assumed to fall as rain. Mean March temperatures projected by GCGM1 and GCGM2 for some of the study sites are above 0° C. This necessitated increasing the length of annual period used to calculate the Fournier index for these sites.

The Wind Erosion Climate Index expresses the erosive potential of climate relative to Garden City, Kansas, which has an annual value of 100% (Lyles, 1983). The index is based on average annual wind speed and Thornthwaite's Precipitation Effectiveness Index, which reflects the climatic contribution to soil moisture and has been previously used in Saskatchewan to investigate the effects of climate change (Williams and Wheaton, 1998). The Precipitation Effectiveness Index requires that monthly precipitation and temperature values be set to 12.7 mm and -1.7 °C if they are below these monthly minima (Lyles, 1983).

Whereas the indices of aridity, wind erosion and rainfall erosivity are a function of climate variables that change at seasonal to decadal time scales, there are other controls on landscape sensitivity that vary significantly within and among study sites, but are static relative to climate variation or, in the case of landcover, treated at static. Aridity and rainfall erosion are strongly linked to soil moisture, which is controlled mostly by soil texture (Bergkamp, 1995). Soil textures classes (Saskatchewan Land Resource Centre, 1999) were ranked from 1 to 5, in terms of water retention and aridity, from the finest and least sensitive soil texture to the most coarse and sensitive texture. The K factor from the Universal Soil Loss Equation (USLE) is a measure of the susceptibility (erodibility) of soil particles to detachment and transport by rainfall and runoff (Stone and Hilborn, 2000). K values were assigned according to textural class using Table K-3 from the handbook of the Revised Universal Soil Loss Equation for Application in Canada (RUSLE-

FAC, 2002).

Slope gradient has a positive influence on rates of erosion. Slope aspect also influences landscape sensitivity as it determines the local distribution of solar radiation, which in turn affects evapotranspiration, the dominant output in the soil water balance. South-facing slopes in the northern hemisphere tend to be drier than other aspects and thus more sensitive to soil degradation. Slope and aspect data were derived from the point elevations and 10 m contours comprising digital 1: 50,000 scale topographic maps. Slope gradient (Ø) was converted to sin Ø, because the gravitational force acting on a slope increases as a sine function of gradient. Since steep slopes are rare in the prairie landscape, all slopes above 30 degrees were assigned a sine of 0.5. In terms of aspect, McKay and Morris (1985) showed that the incoming radiation on a 30-degree south-facing slope at Swift Current, Saskatchewan was about 100% higher than on a north-facing slope and about 50% greater than for east and west aspects and flat surfaces.

The landcover data classified from satellite imagery were reduced to just two classes: land under cultivation and permanent landcover. These represent the two basic categories of agricultural land use and contrasting continuity of plant cover. Because the types of crops on cultivated land change from year to year, this is an over-simplification of the landcover dynamics, but the use of just two classes attempts to deal with the uncertainty concerning changes to landcover over time. The subsequent landscape sensitivity analysis was relatively simple. With tillage and less protective cover, rates of erosion can be an order of magnitude higher on cultivated land compared to land with a continuous permanent cover (Skidmore, 1994; Stocking, 1994), although exposure of cropland to erosion has declined in recent decades with continuous cropping and minimum tillage practices.

Table 5. Range of Factor Values

Factor	Least Sensitive	Most Sensitive
AI	0.5	0.9
Fournier	39	73
Wind Erosion Climate	10	75
Soil Texture	0.01	0.37
Slope gradient	0.0	0.5
Slope aspect	0.5	1.0
Land cover	0	1

To enable combining of the factor data by spatial overlay, irrespective of their original format, all data were standardized from 0 (least sensitive) to 255 (most sensitive) using the last equation listed in Table 4 and the minimum and maximum values for each data set in Table 5. Linear standardization gives the variation in sensitivity among the study sites, which was of primary interest rather than some absolute and ultimately arbitrary value of sensitivity. To account for the relative influence of each factor on landscape sensitivity, they were weighted by pairwise comparison (Saaty, 1977). A pairwise comparison matrix was produced by individually rating pairs of factors on a 9-point continuous scale. The matrix was completed with the rating of all possible pairings. The weights were derived from the principal eigenvector of the square reciprocal matrix of comparisons among factors. Since there are multiple paths by which the relative importance of factors can be assessed, a consistency ratio (CR) is used to express the probability that the matrix ratings were randomly generated (Eastman, 2001). A CR greater than 0.10 indicates that the pairwise comparison matrix should be re-evaluated until the CR is below this critical value. This weighting, while subjective, was based on expert knowledge of land degradation derived from previous investigations of aridity and erosion (e.g., Arnoldus, 1980; Lyles, 1983; RUSLEFAC, 2002; Skidmore, 1994; Stocking, 1994). Weighting was a two-stage process (Figure 2). Primary data layers of individual factors were weighted and grouped into composite factors or secondary layers; that is, climate, soil and landcover. The secondary layers were in turn weighted and overlaid to produce the final results. This process was repeated four times—once for the normal time period and three times for the 2050s—and once for each of the GCMs scenarios of future climate.

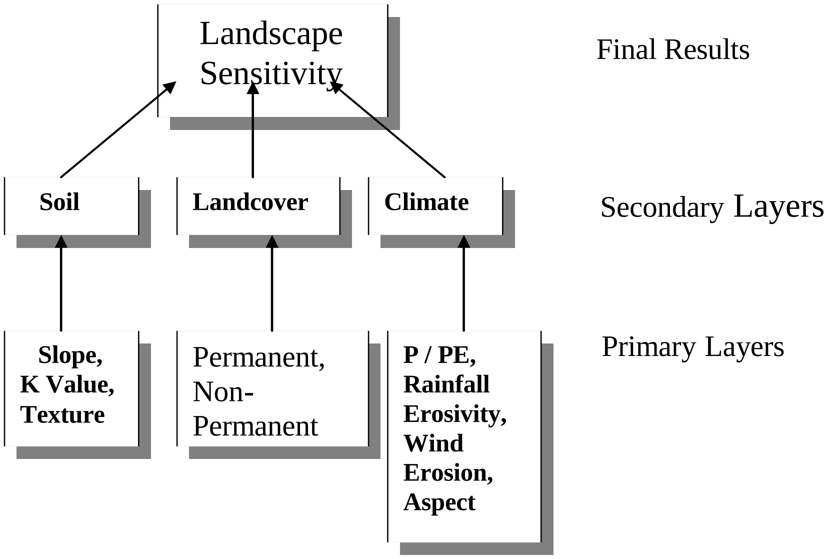


Figure 2. Landscape Sensitivity Hierarchy.

In previous applications of factor weighting and spatial overlay to the assessment of desertification, landscape factors have been weighted equally (e.g., FAO/UNEP, 1983; UNEP, 1992; Basso et al., 2000). This implies that the knowledge of desertification processes is insufficient to weight factors according to their relative influence despite considerable research on the controls of desertification (Bergkamp, 1995; Le Houerou, 1996). Unequal weighting, on the other hand, assumes that it is possible to appropriately weight various controls on a complex process like desertification. Here we take both approaches to determine if the results would be substantially different. Using the hierarchical landscape model (Figure 2), the landscape factors were weighted equally and then differently for the six study sites and the two time periods. The unequal weighting was accomplished using the WEIGHT and Multi Criteria Evaluation (MCE) modules in the IDRISI GIS, which utilizes Saaty's (1977) pairwise comparison method and a consistency ratio. Standardized values for aridity, wind erosivity, rainfall erosivity and aspect were weighted according to their influence on landscape sensitivity, and then combined to produce an overall climate factor for landscape sensitivity. Of the four factors, the aridity factor was weighted the highest while the water and wind erosion factors were weighted equally. In drylands, there tends to be a major response of vegetation and geomorphologic systems to relatively modest changes in the soil water balance (Bergkamp 1995, Le Houerou 1996). Given the relativity low relief of the southern Prairies, aspect was thought to be the least important climatic control on aridity at a regional scale.

Standardized soil factors for slope, soil texture and the K Factor were weighted and combined to produce a secondary layer representing the sensitivity of the soil to land degradation. Soil texture was given the highest weight. In drylands it is a key control on soil moisture and plant productivity (Bergkamp, 1995). The K erodibility factor was given a slightly lower weight. Slope gradient was given the least weight given the generally low relief although it can lead to high rates of valley side erosion. The division of the landcover into only sensitive and non-sensitive classes represents unequal weighting. Of the secondary layers, climate was given a weighting of 0.5 while the landcover and soil layers were each given a weight of 0.25. Only climate changes at the scale of decades and therefore produces a difference in landscape sensitivity between present and future (2050s), while soil and landcover vary over space and account for most of the difference among the study sites.

Results

To present and discuss the results of our spatial modeling of landscape sensitivity, and the impacts of climate change, the numerical results were assigned to five classes of equal size labelled negligible to extreme (Table 6). The data in Table 7 are for all the land in the six study areas. The area of land in each sensitivity class is given for the normal period and for the 2050s as modeled using the three GCMs. The percent change between time slices also is shown. In all cases only a small fraction of the land is in the extreme and negligible categories of landscape sensitivity. With unequal weighting (Table 7a) of the independent variables, the area of land shifts towards lower sensitivity under the two climate scenarios derived from the CGCMs. Both CGCM1 and CGCM2 show an increase of around 9% of the land classified as high sensitivity to over 65% of the total land area. HadCM2, on the other hand, forecasts a large decrease in the high sensitivity category of 24.9% to 31.7% of the total land area, with an increase of 14.3% in the moderate landscape sensitivity category to 42.8% of the total land and an increase of 10.6% to 25.6% for the low landscape sensitivity category. With equal weighting of the landscape factors (Table 7b), sensitivity has a bimodal distribution of high and low sensitivity regardless of the time period and GCM. For CGCM1 and CGCM2, the changes in

Table 6. Landscape Sensitivity Classification

Sensitivity Value	Sensitivity Category
0.0 – 0.2	Negligible
0.2 – 0.4	Low
0.4 – 0.6	Moderate
0.6 – 0.8	High
0.8 – 1.0	Extreme

Table 7. Landscape Sensitivity Results

a) Unequally Weighted: Combined Results

	Normal	CGCM1		CGCM2		HadCM2	
Sensitivity	**%**	**%**	**% Ä**	**%**	**% Ä**	**%**	**% Ä**
Negligible	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Low	14.97	8.35	-6.62	6.96	-8.01	25.56	10.59
Moderate	28.43	25.86	-2.58	27.84	-0.59	42.75	14.32
High	56.60	65.80	9.20	65.19	8.60	31.68	-24.91
Extreme	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	0.00	100.00	0.00	100.00	0.00

b) Equal Weights: Combined Results

	Normal	CGCM1		CGCM2		HadCM2	
Sensitivity	%	%	% Ä	%	% Ä	%	% Ä
Negligible	0.04	0.16	0.12	0.02	-0.02	0.18	0.14
Low	28.10	27.99	-0.11	27.79	-0.31	28.17	0.07
Moderate	7.09	8.82	1.74	5.42	-1.67	14.03	6.94
High	64.77	63.02	-1.75	66.77	2.00	57.61	-7.16
Extreme	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	0.00	100.00	0.00	100.00	0.00

land area from the normal period to the 2050s are less than 2%. For the Hadley model the area of high sensitivity decreased by about 7% to 57% of the total land area with a corresponding increase of 7% to 14% of land in the moderate category.

Results for the individual study sites revealed that, with unequal weighting of factors and the CGCM1/CCGM2 scenarios, the trend for the 2050s was one of increasing sensitivity for all locations. The southeastern study sites of Balcarres and Carlyle had the largest increase, while the more northern sites of Craik and Naicam showed little change and there was a moderate increase at the western study sites of Eastend and Willow Bunch. HadCM2 projected lower landscape sensitivity by 2050s for all study sites. Balcarres, Carlyle and Naicam had the largest decrease; Eastend decreased a moderate amount, and Craik and Willow Bunch the least. For the most part the change in landscape sensitivity for the 2050s using the equal weighting method was minimal, regardless of the GCM.

With the exception of Naicam, the land area in the low sensitivity category decreased from the normal period to the 2050s under the CGCM1 and CGCM2 scenarios and there was an expansion of the moderate category. At Balcarres and Carlyle, the land area in the high landscape category increased 20% to 28%, which came at the expense of the moderate and low categories. However, the other study sites only showed a minimal change in the high landscape sensitivity category. In Willow Bunch and Eastend, the moderate category increased 7% to 14% at the expense of the low category, while in Craik and Naicam there was very little change in the area of land classified in each category from the normal period to the 2050s. HadCM2 forecasted a large increase in the area of land in the moderate category at the expense of the high category for Balcarres, Carlyle, and Naicam. At Craik and Willow Bunch, there was a substantial increase in the low sensitivity category compared to the normal period.

With equal factor weighting, the bimodal distribution of sensitivity is maintained in almost all of the study sites except Balcarres. Generally, there were only minimal changes from the normal period to the 2050s, with CGCM1 and CGCM2 forecasting a small increase in landscape sensitivity, and HadCM2 showing larger change but in the opposite direction: a decrease in high sensitivity with a corresponding expansion of land in the moderate category.

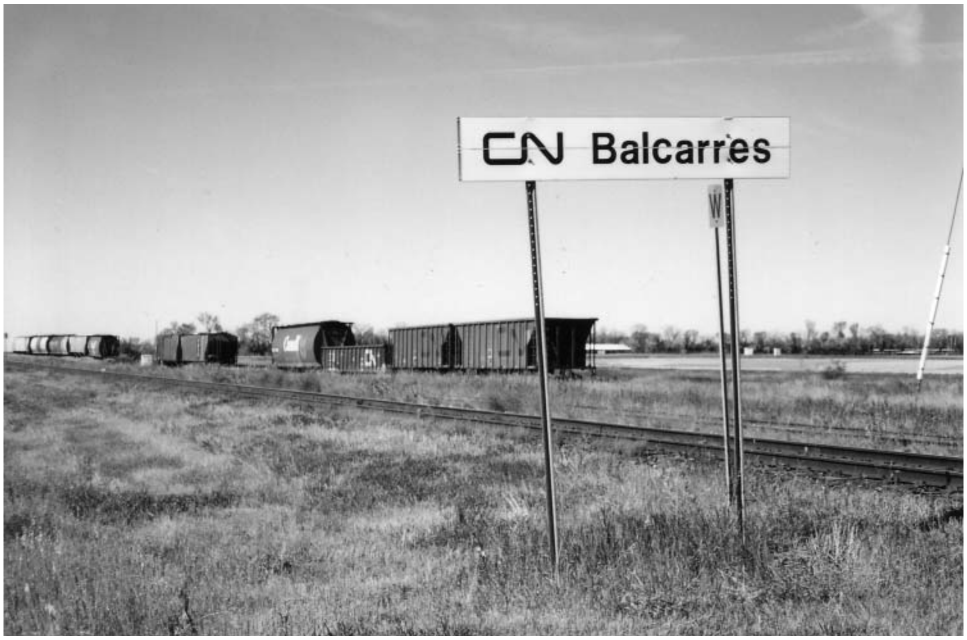
Differences in the two approaches to the weighting of factors were consistent for almost all time periods and GCMs. Unequal weighting classified more land with higher sensitivity, especially in the southwest to south central regions. At individual study sites, there is a more even distribution of land among the sensitivity classes with equal weighting and slightly more land (1–7%) is classified as high sensitivity with unequal weighting. The magnitude of differences between the weighting methods shifts among classes for the two time periods and the GCMs. In the normal time period, equal weighting classified more land in the low and high landscape sensitivity categories. For CGCM1 and CGCM2 and the 2050s, the pattern is maintained but the differences are generally confined to the low category. In contrast, for HadCM2 the differences are concentrated in the high category.

Discussion

This study produced a classification of the current risk of landscape degradation for six study sites and modeled the sensitivity of these landscapes to scenarios of future climate. Since only climate changed from the normal period to the 2050s, any change in landscape sensitivity can be directly related only to the new climatic norms. Landscape sensitivity (risk of land degradation) is predicted to increase for the 2050s compared to the normal time period according to two of the three GCMs used in the investigation. The eastern study sites of Balcarres and Carlyle experience more change in sensitivity than the other study sites. They are located in a grid cell that is nearer the geographic centre of North America where the large change in temperature is forecast by most GCMs.

The higher sensitivity under the CGCM1/CGCM2 climate change scenarios resulted from the higher temperatures and evapotranspiration forecasted by these GCMs relative to the Hadley model. Changes in temperature had more influence on the results than changes in the precipitation. The decreased landscape sensitivity simulated using HadCM2 is attributable to the climate change scenario of slight increased annual temperature with a large increase in annual precipitation. The future climate simulated by CGCM1 and CGCM2 is more alike in terms of temperature than precipitation. The similar forecasts of landscape sensitivity from CGCM1 and CGCM2, regardless of the weighting method, suggests that another GCM that may have been a better choice than CGCM2 for a mid-range scenario between the CGCM2 and HadCM2 models. Therefore, the results with CGCM1/CGCM2 and HadCM2 are probably better viewed as extreme scenarios with the more plausible outcome being somewhere in between.

The distribution of landscape sensitivity, regardless of the weighting method, was heavily influenced by the landcover. The use of two land-use options, lands under some form of cultivation and those with permanent landcover, forced the landscape sensitivity



Balcarres, Saskatchewan, 2005. Courtesy David McLennan.

results into a bimodal distribution, especially with equal weighting of the factors controlling land degradation. In the study region, more land is cultivated than with permanent cover and thus more land was classified with higher sensitivity. The Eastend study area is almost evenly divided between the two landcover classes and thus landscape sensitivity results, with equal weighting and for the normal time period, is almost evenly divided between high and low sensitivity. Because unequal weighting of the causal factors placed less emphasis on land cover and more emphasis on climate factors, it was perhaps the preferred approach. It also enables the weighting of factors according to knowledge of the controls of land degradation as described in the literature. The inherent subjectivity in the factor weighting and spatial overlay method has to be recognized, although there are few viable methodological alternatives. Investigating landscape sensitivity on a coarser spatial scale would allow for use of a more comprehensive database and more seamless integration of some of the coarser data sets used in the investigation. It would require, however, a re-evaluation of the landscape factors used in the investigation because, as the spatial scale changes, those landscape properties that are important to a process change.

Land degradation and desertification are related as much to land management as climate (Le Houerou, 1996; Darkoh, 1998). Therefore, for example, the record of sedimentation from a small lake in eastern Saskatchewan showed a more definite erosional response of the basin to land use than to climate, with a rapid increase in sediment input with settlement, and declining sedimentation with the widespread use of soil conservation practices starting in the 1960s (de Boer, 1997). Given the role of land use in determining landscape sensitivity, land management issues come to the fore when trying to limit the impact of degradational forces on landscapes. Identifying the potential for climate-related changes in risk of land degradation supports planning and practices to limit climate change impacts on soil landscapes. The methods and analysis applied here could be repeated for any and all communities in the prairie region since there is a common database of climate, topography and soils. Demonstrating and evaluating the sensitivity of soil landscapes to fluctuations in climate has policy implications in terms of ensuring that land use and management in the more sensitive areas do not elevate the risk of desertification under climate change.

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