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The Climate Sensitivity of the Soil Landscapes of the Prairie Ecozone

Final Report

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TABLE OF CONTENTS

1 Executive Summary

The project reported here examined sensitivities of prairie soil landscapes to climate change, variability and extreme hydroclimatic events. Early in the project, a review of existing climate impact assessments and methodologies suggested that most are based on an incomplete understanding of the climate forcing of geomorphic systems, especially in relation to the influence of scale on the understanding and modeling of biophysical systems. Therefore a high priority was given to developing a practical framework for the assessment of potential impacts of climate change on the soil landscapes of the Canadian plains. This framework 1) facilitates transfer of the results of scientific research to stakeholders for the planning of adaptation to soil landscape sensitivity, and 2) is spatially-explicit, unlike models and methods that lack geographic reference and thus direct application to the real world. This approach to climate impact assessment requires a spatial data model and a model of the geomorphic response to climate. Since landforms are the product of geomorphic processes, assemblages of landforms and the associated soil profiles, are the geographic expression of a geomorphic systems. The use the soil landscape as a spatial data structures expands climate impact assessment beyond the study of soil loss or and beyond the farm or field. Conventional approaches to the assessment of soil erosion risk, estimating potential soil loss from fields, will not support the integrated planning over large areas or thus the adaptation to the impacts of climate change.

The response of geomorphic systems to climate is complex. Long periods of landscape stability are interrupted by short bursts of erosion as s system responds to the forces of a hydroclimatic event that exceeds a geomorphic threshold. Irreversible landscape change can occur in response to single events. Much of what we know about the climatic forcing of natural systems is based on detailed field experiments conducted over small areas in contrast to the scale of land and water management. A "scaling down" of climate and a "scaling up" of process data is required for the study of climate impacts on soil landscapes. Most process simulation models fail to work when scaled up because of the greater complexity of larger systems and non-linearity caused by feedback among system variables, and the emergence of characteristic patterns and processes at coarser scales. Virtually all existing models of soil loss and landscape change are inappropriate for the spatial analysis of the climatic forcing of surface processes in the Canadian plains. The greatest promise for a model-based approach lies in relatively simple physically-based models, because they are more scale robust than empirical models (*i.e.* derived from the measurement of erosion from plots) or the data-rich analytical modelling of slope and channel processes. Models reduced to a form that capture essential or salient factors are most easily applied to assessment of soil landscape sensitivity at a regional. In fact dimensionless indices are simple and practical, yet meaningful, models of landscape sensitivity. Mapping the Aridity Index (Precipitation / Potential Evapotranspiration) for 1961-90 and the 2050s demonstrates the the area of land at risk of desertification will increase by about 50%.

In managed landscapes erosion is mostly a socio-economic issue since erosion can be prevented by soil conservation, but capability and willingness to implement soil conservations are governed by a host of social and economic factors. Even though rates of erosion are managed, land managers must realize that landscape change is a threshold process, such that the conditions that lead to land degradation are established before they are recognized. An increase in the probability of extreme erosion evens, as the result of climate change, above "once in a lifetime" may justify increased use of soil conservation.

The most practical yet rigorous methodology for assessing of the climate sensitivity of prairie soil landscapes is to "serve" a georeferenced data base such that stakeholders are able to derive maps interactively and apply simple climate change scenarios to geo-referenced data, targeting sensitive soil landscapes. This approach requires 1) definition and analysis of scale domains and thresholds that determine the relevant parameters at a given scale and also enable the scaling up from landforms to landscapes, and 2) a methodology for classifying and identifying soil landscapes according to primarily geomorphic criteria. These problems are the basis for two M.Sc. theses scheduled for completion during 2002. In the meantime, we have implemented the Internet Map Server technology that will enable us to serve the resulting database at the PARC web site. For demonstration purposes, the IMS has been applied to the existing coarse scale Soil Landscapes of Canada, to detailed soil survey and to other public-domain georeferenced databases.

Our PARC Quick-Start project has produced 1) a more thorough understanding of the conceptual and technical issues related to a rigorous and spatially-explicit evaluation of the impacts of climate change on soil landscapes, and 2) a practical framework for enabling this evaluation and the planning of adaptation to minimize the impacts of soil landscape sensitivity on agriculture, forestry and water quality. The concrete deliverable is the interactive map services available at the PARC web site (www.parc.ca), where researchers and stakeholders can apply simple climate change scenarios to geo-referenced data, targeting sensitive soil landscapes.

2 Introduction

Climate change impacts and adaptation generally are examined by sector: agriculture, forestry, energy, health, settlements, fisheries, ecosystems (biodiversity), and water resources (IPCC, 2001, UNEP, 1998). Whereas water receives separate and extensive treatment, impacts on soil usually are examined in the context of agriculture and, to some extent, forestry and terrestrial ecosystems. Adverse climate change impacts on soil resources include degradation, loss of productivity, and desertification. According to the IPCC Working Group II (2001: 32), a high probability that soil degradation will be intensified by global warming has been established with high confidence and therefore "a critical research need is to assess whether resource [soil] degradation will significantly increase the risks faced by vulnerable agricultural and rural populations".

On the Canadian Plains (Figure 1), global warming is expected to decrease available soil moisture and soil productivity. More extreme climate and related disturbances could lead to a further soil degradation and loss of productivity. As with most other natural and social systems, the greatest threat to the stability of soil landscapes is posed by extreme climate. Higher magnitude hydroclimatic events are more likely to exceed natural and engineering thresholds beyond which the impacts of climate change are much more severe. Temperature or precipitation trends (climate change) do not cause landscapes to immediately respond. Rather, most change in social and biophysical systems occurs as the result of extremes of climate and to short-term departures from average conditions (climatic variability).

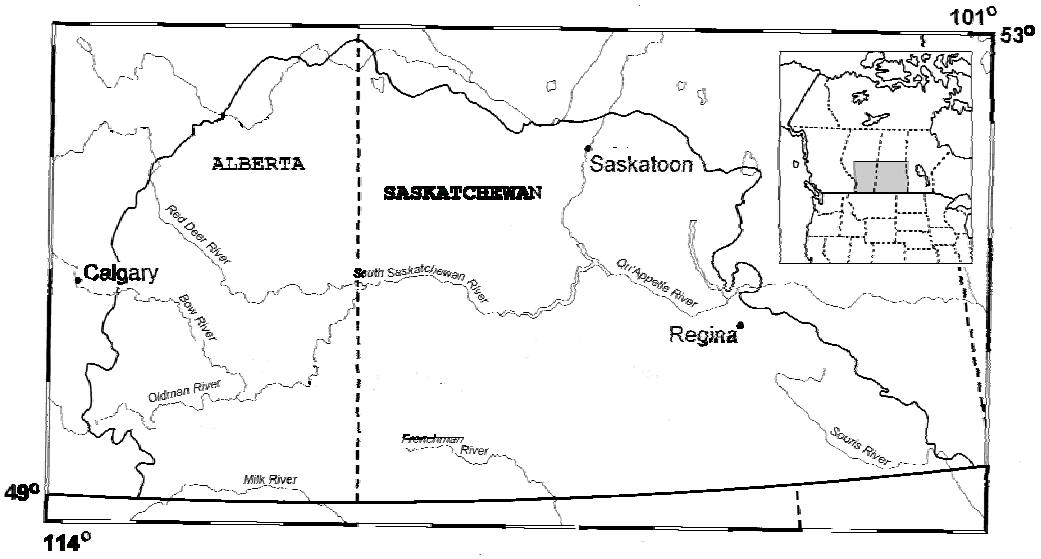

Figure 1. The Prairie Ecozone delineated by the bold line.

Strong temperature seasonality and large interannual climate variation is characteristic of the world's mid-latitude continental interiors. These dry lands also tend to have sensitive soil landscapes, that is, there is a high "likelihood that a given change in the controls of a system will produce a sensible, recognizable and persistent response" (Brunsden and Thornes, 1979: 476). Semi-arid landscapes have among the highest rates of erosion and sediment yield (Bull, 1991). Therefore, shifts to drier climatic conditions, whether short term (drought) or climate change, result in increased sediment production (Knox, 1984). Because the soils and climate are less productive than in more humid regions, the agricultural use of drylands also tends to be sensitive to climate: "Typically, sensitivity to weather is greatest firstly in developing countries … and secondly in those regions where the main physical factors affecting production (soils, terrain, and climate) are less suited to farming. A key task facing those concerned with conducting impact assessments is to identify those regions likely to be most vulnerable to climate change, so that impacts can be avoided (or at least reduced) through implementation of appropriate measures of adaptation." (Perry *et al*., 1998 : 8-2).

Adaptation refers to "the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate." (IPCC, 1996). Conversely, maladaptation is the result of "actions which tend to increase vulnerability to climate change" (Burton et al., 1998). Since natural systems have responded spontaneously to millennia of climate change and variability, they are generally better adapted to climate than managed landscapes. The maladaptation of agriculture and forestry to the climatic forcing of geomorphic processes is manifest as accelerated rates of soil erosion. This global problem generally is exacerbated by climate change, with ... Thus adaptation of these sectors to climate includes protecting soil landscapes from the impacts of extreme hydroclimatic events and climatic variability. Soil conservation is a prime example of a 'no regrets' strategy, since preventing soil loss is beneficial, whether or not global warming occurs as forecast. Soil conservation practices can be defeated, however, by climate change: "Severe and widespread erosion could still occur during extreme climatic events and especially during a period of years with back-to-back droughts" (PFRA, 200). Ability to adapt also is subject to availability of means and the distribution of cost (IPCC, 2001). In most jurisdictions, the cost of soil conservation is borne primarily by the land manager. "Very severe wind and water erosion is dominated by infrequent occurrences of when highly erosive events impact exposed soil. Such events may only happen once during the farming lifetime of an individual farmer, making it difficult to justify the expense and inconvenience of many soil conservation practices." (PFRA, 2000: 33).

Natural biophysical systems will be subject to increased disturbance as unprecedented rates of climate change and degrees of climate variability cause ecological and geomorphic thresholds to be exceeded. The vulnerability of these unmanaged systems is expected to increase with time since adaptation is limited to the spontaneous adjustment to climate. Managed systems include management structures to buffer the impacts of climatic change and variability. Land use and management have greater impact on soil landscapes than climate change (Jones, 1993), and they have the potential to significantly mitigate the impacts of climate. Management of surface cover, including restoration to its original condition (Carter et al., 1994), is the most practical strategy for adapting land use practices to minimize the adverse effects of climate on soil landscapes. The engineering of physical systems, on the other hand, tends to be costly and ultimately futile, since geomorphic processes can be controlled only to a certain extend and only on engineering time scales. Climatic variability and extreme events can't be managed, only vulnerability by increasing resistance or avoidance where the potential for disturbance is high.

Despite the vast area and relatively sparse population of the Canadian Prairie Provinces, most of the landscape is managed. An expansion of agriculture into the currently forested margins of the Prairie Ecozone will require assessment of the sensitivity of these soil landscapes to both climate change and a changed surface cover. Conversely, the soil landscapes of the semi-arid southwestern plains may become more marginal for agriculture at a greater risk of degradation. Forest and farm management practices enable adaptation to climate change, however, a much better understanding of the climate sensitivity of soil landscapes will be required, as will improved methodologies for the modeling and mapping of climate impacts in a manner that is transferable to planning and policy making. Conventional approaches to assessment of soil erosion risk, estimating potential soil loss from fields or cut blocks, will not support the integrated planning over large areas of adaptation to the impacts of climate change.

2.1 Objectives

Because adaptation planning must address the key and obvious question "Adaptation to what?", climate change impact assessment is a necessary precursor to establishing adaptation strategies. The project reported here is an analysis of the sensitivity of soil landscapes of the Canadian plains to climate change. Early in the project, a review of existing climate impact assessments and methodologies suggested that most are based on an incomplete understanding of the climate forcing of geomorphic systems, especially in relation to scale and in contrast to the response of ecosystems to climate. Therefore, it became clear that a meaningful and valid analysis of the potential impacts of climate change on soil landscapes necessitated an analysis of the limitations of existing methodologies and a new framework for impact assessment and adaptation planning that is both practical and based on a sound understanding of the climate forcing of geomorphic systems.

Therefore, the principal **objective** of this project has been to develop a framework for the assessment of soil landscape sensitivity that

1) facilitates the transfer of results of modeling and research to stakeholders for the planning of adaptation to climate change that accounts for soil landscape sensitivity, and
2) is spatially-explicit, unlike models and methods that lack geographic reference and thus direct application to the real world.

3 The Geomorphology of the Interior Plains

Landforms and soils differ significantly among the geologic provinces of the Canadian interior: the plains, shield and cordillera. This report considers only the soil landscapes of the Interior Plains, which dominate the Prairie Provinces, encompassing all the agricultural land use and most of the commercial forest. The Interior Plains includes a variety of landscapes, (*e.g.* meltwater valleys, till plains, dunes fields, glacial lake plains, ice-thrust hills) with distinctive geomorphic histories and responses to climatic variability and change (Lemmen *et al*., 1998). This subhumid region or Prairie Ecozone (Figure 1) is well suited to a study of the climate forcing of landscape change, because subhumid landscapes are sensitive to changes in the climatically-driven surface water balance (Lemmen and Vance, 1999). Prolonged dry or wet weather influences the resistance of soil and vegetation to major hydroclimatic events (Sauchyn and Skinner, 2001; Wolfe, *et al*., 2001).

Late-Pleistocene glaciation of the interior plains created a landscape which differs significantly from the boundary conditions assumed by most models of the climatic forcing of geomorphic processes (c.f., Kirkby, 1993; Willgoose et al., 1992). With a short geomorphic history and dry climate, the landscape is poorly integrated and the sediment budgets of slopes and channels are mostly unrelated or "decoupled" (Phillips, 1995). Significant geomorphic activity, in dune fields, cropland, and large meltwater valleys (Lemmen *et al*., 1998), tends to be isolated by the lack of permanent streamflow and poorly-integrated drainage network. As a result, rates of erosion on cropland are 2-3 times higher than sediment yields in small watersheds (Carson & Associates, 1990). Water erosion mostly redistributes soil locally, especially in the extensive areas of hummocky and rolling moraine (Pennock and de Jong, 1995). There are few permanent

streams. Large areas are internally drained by intermittent stream flow into shallow saline lakes. Lacking are the order and characteristic structure of a landscape dissected by an integrated stream network, except over small areas which have evolved rapidly since deglaciation. At a regional scale, these small areas are segments of larger landscapes. For example, badlands are scattered throughout the valley networks.

The climatic forcing of the geomorphic systems of the Interior Plains is understood from studies of Holocene climate and landscape change and the monitoring of climate and geomorphic activity. These studies and forecasts of future climate lead to speculation on the impacts on climate change on eolian (Wolfe and Nickling, 1997) and fluvial geomorphic systems (Ashmore and Church, 2001). The Canadian Centre for Climate Modelling and Analysis' transient climate change simulation suggests that the largest CO_2-induced rise in mean surface temperature in southern Canada will occur in the Interior Plains (Boer *et al.*, 2000). A regional climate model for western Canada forecasts similar trends (Laprise *et al*., 1998). Most general circulation models (GCMs) forecast increased winter precipitation but with decreased net soil moisture and water resources in summer. Predictions of precipitation, however, are less certain than those for temperature (Herrington *et al.*, 1997: 16-17). This weakness in climate prediction is critical for the prairie region, where the variability of precipitation is characteristically large and has a profound impact on natural and human systems. Climate change scenarios also suggest more frequent extreme conditions including drought and major hydroclimatic events (Hengeveld, 2000). Instrumental records for the prairie provinces show statistically significant trends in various climate variables (Akinremi, *et al*., 1999; Cutforth, *et al*., 1999; Zhang *et al*., 2000). Gullett and Skinner (1992) documented a statistically significant increase in temperature over the past century for the prairie provinces. These studies indicate a change in hydroclimate in early spring with an earlier snowmelt season. This implies a shift in hydrologic and geomorphic activity with a longer snow free season during which soil is exposed to rainfall erosion.

Decreased net soil moisture under global warming suggests accelerated wind erosion and sand dune activity. Extensive areas of sand dunes characterize the more arid areas of the southern Canadian plains, especially between 50° and 51°N, and include the Great Sand Hills of southwestern Saskatchewan (David 1993). Activation of sand dunes is related to aridity and reduced vegetation cover (Vance and Wolfe 1996). Wolfe *et al*. (1995) documented the critical role that soil moisture plays in the stabilization of dunes, showing that dunes in the Great Sand Hills have a rhythm of reactivation in the last fifty years matching the pattern of droughts. Significantly, dates from this region define an interval of no dune activity between 560 and 220 years ago, perhaps due to moister LIA conditions. Conversely, optical dating indicates sand dune activity between about 1000 and 900 years ago and since about 200 years ago, related to the drought of the 1790's that stands out in tree ring records (Wolfe *et al*., 2001). In the Brandon Sand Hills, David (1993) identified ten intervals of drought in the last 4300 years, including three (1100, 850, and 400 yr BP) in the last millennium. Intervals of prolonged drought (Sauchyn and Skinner, 2001) and associated sand dune activity, such as the late 18th century (Wolfe *et al*., 2001) serve as temporal analogues of potential future response of eolian systems to climate change and variability. Current sand dune activity in the dry core of the Palliser Triangle serves as a spatial analogue of potential response of currently stable dune fields on the currently moister margins of the Prairie Ecozone and southern Boreal Plains (Thorpe *et al*., 2001).

Streams that are fed wholly from sources within the plains may be expected to be more responsive to changes in precipitation, than the rivers that are derived from snowmelt in the Rocky Mountains and account for an estimated 70% of the mean annual discharge of the major river systems draining the southern Canadian plains (Campbell 1996). The climate sensitivity of prairie fluvial geomorphic systems is recorded in late-Holocene sedimentary and morphologic records. Ghostpine Creek, a tributary of the Red Deer River, cut down 4-5 m from a former terrace level and aggraded, partly simultaneously, up to 3 m since about 2600 yr BP (Rains *et al.*, 1994). In the Falcon Creek valley, Dinosaur Provincial Park, an interval of channel aggradation, beginning around 800 - 600 yr BP and lasting until sometime after around 300 yr BP, was preceded by a mid to late Holocene interval of incision and followed by renewed incision after about 300 yr BP (O'Hara and Campbell, 1993). These changes at Falcon Creek seem to coincide with two main climate phases recognized from lacustrine records (Lemmen and Vance, 1999), however, correlating low-resolution paleolimnology and alluvial stratigraphy is problematic, given the complex and much different responses of geomorphic systems and aquatic ecosystems to climate (Vreeken, 1999).

Landslides are of major formative importance in the evolution of the Holocene valleys of the Interior plains (De Lugt and Campbell, 1992; Mollard, 1977). The geology and geomorphic history strongly favours mass wasting. Most slopes have developed since regional deglaciation in poorly- consolidated surficial materials. The perception of the prairie landscape as geomorphologically inert contrasts with the significance of mass wasting as a process of Holocene landscape modification. Landslides are "ubiquitous" in the major river valleys. With a drier future climate, slope stability could be limited to undercutting of valley sides by streams and shallow mass wasting during major hydroclimatic events (Sauchyn, 1998).

4 Modeling Landscape Sensitivity

> Sensitivity to climate stimuli is still poorly quantified for many natural and human systems. Responses of systems to climate change are expected to include strong nonlinearities, discontinuous or abrupt responses, time-varying responses, and complex interactions with other systems. However, quantification of the curvature, thresholds, and interactions of system responses is poorly developed for many systems. … Continued efforts to detect impacts of observed climate change is a priority for further investigation that can provide empirical information for understanding of system sensitivity to climate change (IPCC 2001: 73).

Strong nonlinearities, discontinuous or abrupt responses, and time-varying responses characterize the climate forcing of geomorphic processes (Favis-Mortlock and Boardman, 1995; Appendix B). Irreversible landscape change can occur in response to single hydroclimatic events. The hydraulic conductivity of soil is a critical threshold below which rain and snow melt water usually infiltrate the surface which erosion is absent and above which rates of water erosion increase exponentially with linear increases in rainfall. The equivalent threshold for wind erosion is the critical wind speed for the movement of soil particles. Beyond these thresholds, the geomorphic response tends to be disproportional to the magnitude of rain or wind, and depends very much on antecedent conditions, that is, the recent history of the soil landscape.

This includes the impacts of preceding hydroclimatic events and the more gradual lowering of resistance while the landscape is apparently stable, for example, from disturbance of soil or waning of vegetation cover. Thus, while landscape sensitivity varies continuously, landscape change tends to occur episodically, trigged by major hydroclimatic events. This climate sensitivity is the basis for the inference of environmental change from sediments (Goudie, 1992), which record a history of geomorphic and hydrologic response to climate variability and change. Landforms and, at a coarser scale, landscapes are the spatial expression of geophysical processes acting over geologic time, while soil is the product of biophysical processes operating on stable landforms. (Thus soil landscapes are the appropriate geographic units for the study and assessment of climate change impacts on geomorphic systems, as discussed further in section 4.1.) Whereas rrepeated episodes of erosion are required to create landforms over geologic time, a single erosional event can have devastating consequences for farming or forestry. Centimeters of topsoil can be removed during a single episode of wind or water erosion, reversing centuries or millennia of soil development and rendering land unproductive. Long periods of landscape stability are interrupted by short bursts of erosion, lasting only hours or days.

4.1 Spatial Modeling

Climatic change research challenges earth scientists and ecologists to apply their understanding of biophysical processes measured over small areas (plots, slopes, stands, *etc*.) to the modeling of processes at a landscape scale (Running *et al*., 1989; Sugden *et al*., 1997; Vitek and Giardino, 1993). Studies of climate impacts can be categorized according to the degree to which place, scale and spatial heterogeneity are recognized:

1. spatially implicit: forecasting change to biophysical systems without specific reference to location, e.g., impact of climate change on the boreal forest
2. spatially discontinuous: evaluating models at points and interpolating among these locations, e.g., climate stations or grid intersections
3. spatially continuous: evaluating a model (e.g., soil erosion risk) by map unit
4. spatially continuous and explicit: modeling the spatial distributions of specific variables, e.g., the spatial distributions of disturbance and resistance

A geographic information system (GIS) and digital geographic data enable the fourth approach, but also facilitate the extrapolation of models, and associated concepts, to landscapes and scales not represented by the digital data base. The aggregation or patching together of the results of small area studies, and extrapolation from the fine scales over large areas, usually is invalid because the relevant and dominant variables change with scale. The implications of scale for climate impact assessment became of major theme of our project. This theme was explored in a journal publications and an unpublished manuscript (Appendices B and G). Scale is a sufficiently significant problem in climate impact assessment that it is the subject of a masters thesis arising from this project, as described in Appendix F.

Systems that are modeled with the fewest variables are those that are furthest removed from the scale of human perception: the astronomical and the microscopic. Scientists can predict the position of the planets with greater precision and accuracy than the state of next week's weather. Global climate change has been described as "the ultimate scale issue" (Peterson and Parker, 1998). The reductionist approach to complexity of nature is to model systems at the finest scales, where phenomena are accessible to mechanistic theory.

Much of what we know about the climatic forcing of natural systems is based on detailed field experiments conducted over small areas in contrast to the scale of land and water management in regions like the Canadian plains. A "scaling down" of climate and a "scaling up" of process is required to link the modeling of climate at coarse scales to biophysical processes at finer scales (Bass, et al., 1996; Hostetler, 1994; Kirkby et al., 1996; Sugden *et al*., 1997). Most process simulation models fail to work, however, when scaled up because of the greater complexity of larger systems and non-linearity caused by feedback among system variables, and the emergence of characteristic patterns and processes at coarser scales (Haff, 1996). For all kinds of geographic data, responses or measurement obtained over small areas often produce results and conclusions that differ or even conflict when the data are aggregated to represent larger areas. In spatial analysis, this influence of scale on the processing and understanding of geographic data is known as the Modifiable Areal Unit Problem (Klinkenberg, 2001),

The geographic expressions of geomorphic processes, landforms, are not mapped systematically over large areas. Therefore, a suitable spatial data structure for modeling geomorphic systems at coarse scales is largely on the availability of topographic and soil data covering large areas derived digital satellite data and air photo interpretation (Running, et al., 1989; Sauchyn, 1997). The mapping of surficial geology, at least in Canada, tends to be at relatively small map scales given the size of the country. Also classification schemes and map legends can vary among mapping agencies. The genetic classification of surficial materials has geomorphic relevance, although current geomorphic processes represent the redistribution of mostly glacial deposits by wind and water. Soil maps also capture landforms, because topography is a primary control on soil formation and geography at larger map scales. Furthermore, because soil mapping has been largely confined to the small proportion of Canada, which is arable land, soil surveys are based on relatively detailed mapping and a consistent classification scheme (Expert Committee on Soil Survey, 1987). Given the relevant nature and scale of these soil surveys, the soil landscape and soil landscape unit are the most useful concept and construct, respectively, for the modeling of the sensitivity of geomorphic systems to climate. They expand the perspective from soil, and the crop production and the farm unit, to include the spatial characteristics of hydrologic, ecological and geomorphic systems. The fundamental basis of soil classification and mapping is the soil forming factors of climate, vegetation, parent materials, topography and time. Thus the emphasis is on the origin of the soil and, from an agricultural perspective, the productivity of capability of the soil to support crop production or grazing. This is reflected in the physical and chemical attributes measured and assigned to soil map units. Physical data, specifically soil texture and hydraulic conductivity, determine soil erodability. The redistribution of soil at a landscape scale, however, requires information and variables that are conventionally not used in the mapping of soils: drainage at a watershed scale.

The critical factor controlling soil landscape sensitivity is the soil water balance. The area of land at risk of desertification, defined by a ratio of precipitation to potential evapotranspiration of less then 0.65, will increase by 50% between current conditions (1961-90) and the 2050s. This is illustrated in Figure 2, where the Aridity Index (P/PE) is mapped using climate data for 1961-1990 and then using outputs from the Canadian GCM1 for the 2049-2060. While this map provides a coarse level perspective on potential soil erosion, at a finer scale landscape sensitivity varies according to topography and soil. Figure 3 illustrates the large difference in drainage pattern in the prairie landscape between a fluvially-dissected area and adjacent morainal landscape lacking in drainage.

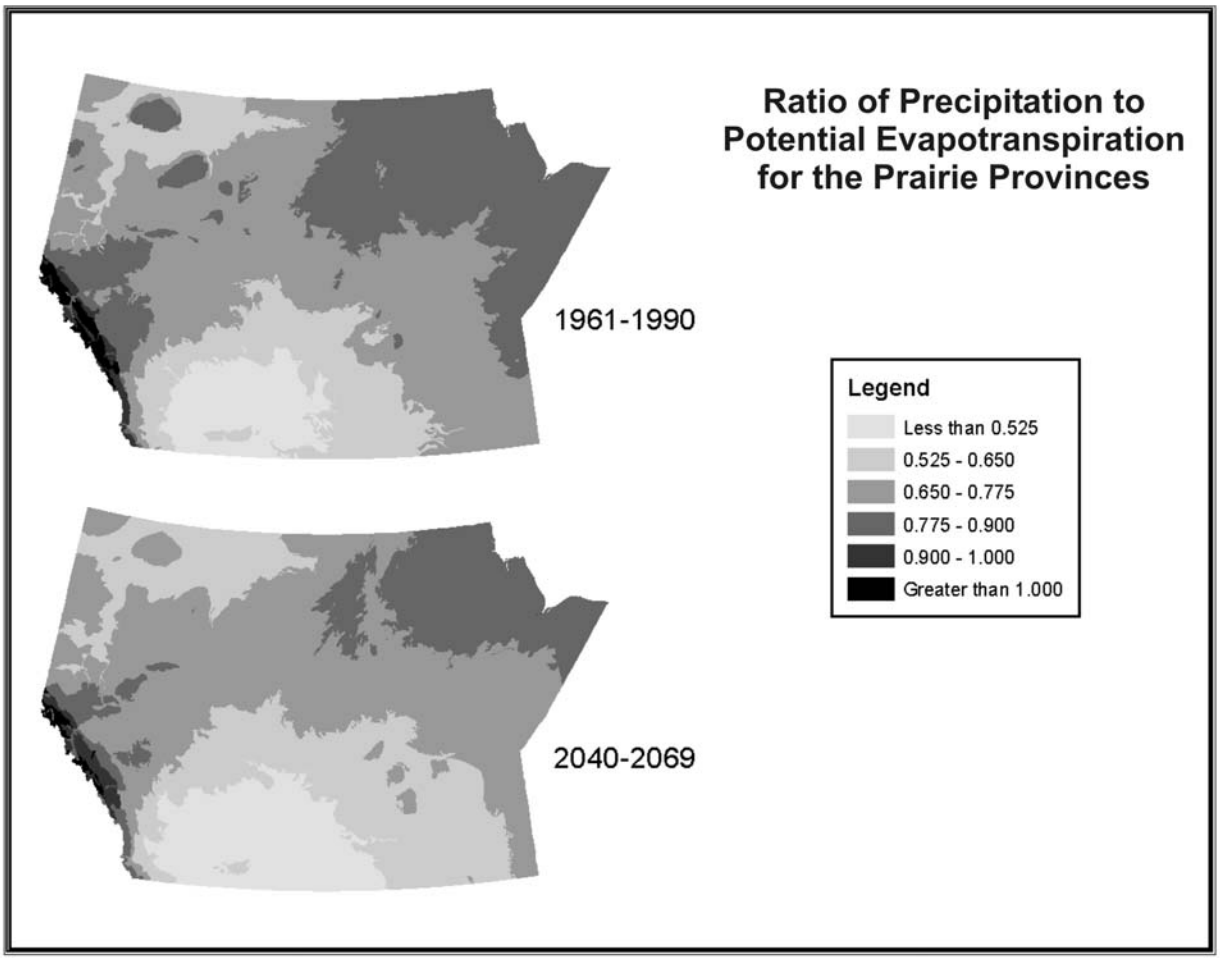

Figure 2. Maps of the Aridity Index using climate data for 1961-90 and output from the CGCM1 for 2040-2069.

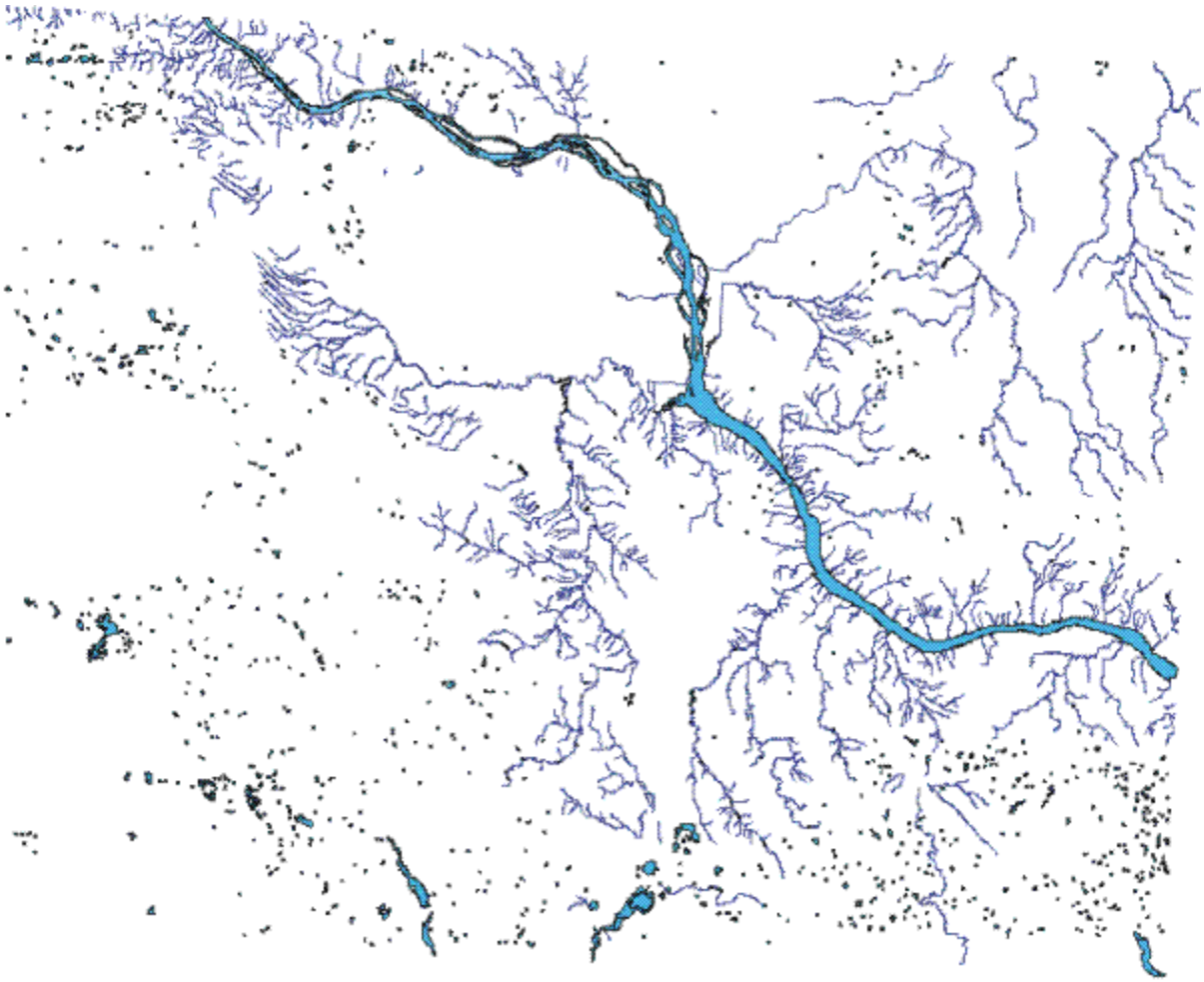

Figure 3. A hydrographic map showing the contrasting drainage between the dissected landscape near the South Saskatchewan River valley and the lack of drainage on the adjacent prairie surface (lower left) where the primarily depression storage (sloughs and small lakes) is characteristic of much of the glacial landscape of the Interior Plains.

Soil landscape is a key concept in the field of soil geography (Buol et al., 1980; Hole, 1978). In a textbook devoted to "the study of the soil landscape from a geographic perspective (p. xv)", Hole and Campbell (1985) concluded from a literature review "that soil landscape, and the abbreviation soilscape, are of value as general introductory terms, but perhaps not as specific ones" (p. 12). Accordingly, they used a broad definition: "the total mass of unconsolidated geologic and pedologic material ". Application of this concept to soil survey, however, requires an operational definition: "The full array of attributes that describe a distinct type of soil and its associated characteristics, such as landform, slope, water table, permafrost and lakes, is called a soil landscape" (Shields et al,, 1991: 5). In lieu of geomorphic maps, and despite the predominantly agricultural applications of soil surveys, soil landscapes are the closet common map unit to a geographic expression of geomorphic systems and thus serve as the spatial structure for our modeling of the regional geomorphic response to climate change and variability.

The concept of soil landscape as defined by soil scientists place the perspective on soil origin and productivity: "The full array of attributes that describe a distinct type of soil …" (Shields *et al*., 1991: 5). Soil series are compiled from the synthesis and classification of soil properties. This suits very well the application of soil landscape maps and databases to agricultural issues, such soil capability and impacts of climate change on soil productivity and crop production. A geomorphic perspective on soil landscapes requires a shift in emphasis from the pedon to landforms: The full array of attributes that describe a distinct assemblage of landforms and the associated soil series and hydrologic characteristics. These types of soil landscapes could be mapped the synthesis and classification of geomorphic data. As a means of scaling up soil and geomorphic properties, this spatial synthesis would result in the best spatial data structure for the assessment of the climate sensitivity of soil landscapes. Therefore, one thread of research arising from this current project is developing a methodology for the compilations of synthetic landscapes and geo-referenced geomorphic databases (see Section 6 and Appendix E).

4.2 Process Modeling

Many models have developed to predict or simulate erosional processes at various scales and for managed and unmanaged landscapes. A major distinction can be made between the modeling of landscape evolution (geomorphic models) and soil loss from managed (mostly agricultural) landscapes, either annually or for storm events.

A new generation has soil loss models have been developed to replace the traditional and widely applied Universal Soil Loss Equation (USLE) and Wind Erosion Equation (WEQ). The water erosion prediction project (WEPP; Flanagan, *et al*., 2001) is a continuous, process-oriented erosion simulation model. It simulate small profiles up to large fields and is applicable to small watersheds. It mimics the natural processes that are important in soil erosion. Everyday it updates the soil and crop conditions that affect soil erosion. When rainfall occurs, the plant and soil characteristics are used to determine if surface runoff will occur. If predicted, then the program will compute estimated sheet & rill detachment and deposition, and channel detachment and deposition. The WEPP can be applied to hillslopes (a direct replacement for the USLE), watersheds (field-sized areas up to about 640 acres).

The Wind Erosion Prediction System (WEPS; Wagner, Larry E. 1996) is a daily simulation model that integrates the specific factors of weather, crops, tillage, and soils to compute soil erosion and deposition. It is applicable to just one field, or can be applied to a few adjacent fields. When wind speed exceeds a threshold, the EROSION submodel of WEPS simulates soil loss and deposition on a sub-hourly basis. Sensitivity tests of the simulation equations indicate that soil loss by wind erosion was most sensitive to wind speed and surface-soil moisture content.

In contrast to the erosion models developed and used by agricultural scientists, geomorphologists model erosion to explain the evolution of landforms. Usually either landform evolution over time or space is modeled since to incorporate both dimensions would be extremely complex. . Traditionally time-dependent models were more readily accepted because they were compatible with the popular notion of biological evolution and slow change over time and qualitative descriptive investigation. A time-independent perspective is based on the concept of the geomorphic systems and a dynamic equilibrium between rates of geomorphic processes and the

forcing factors, mostly climate-related. This approach assumes that earth history (time) is not relevant and therefore is applied over relatively small areas (slopes or small watersheds) over which the geomorphic systems can be modeled in terms of controls (e.g., climate), process, resistance and response (sediment yield and morphological change), without invoking the history of the system. This is problematic for the modeling of regional landscape sensitivity; as noted elsewhere in this report, climate change challenges geomorphologists to scale up models to larger areas over which landscape history becomes a factor.

For the past several decades, the foremost modeler of geomorphic process has been Professor Michael Kirkby of Leeds University, U.K. (Kirkby, 1993; Kirkby & Cox 1995; Kikby *et al* (1996.). His slope model is based on a mass balance equation formulated using differential calculus so that, the slope is modeled simultaneously as a continuous profile. Variation in elevation is modeled as a function of mechanical and chemical transport processes. The simulation of weathering is based on the concept of a soil deficit: the amount of material required to reconvert soil into bedrock. The soil profile model is primarily chemical in nature and strongly dependent on the effects of hillslope hydrology on chemical weathering and solute transport. The rate of change in chemical removal is constant with respect to changes in the volume of subsurface flow. Other important concepts include erosion-limited removal: from transport-limited where the actual transport rate is equal to the transporting capacity of the process versus weathering-limited where the capacity of the transporting process greatly exceeds the transport rate. A hydrological submodel based on annual precipitation, mean rain per day, surface storage capacity and evapotranspiration combined in a mass balance.

Kikby *et al* (1996) dealt with the scaling of geomorphic models by advocating simple physical based models of regional climate parameters. The Cumulative Soil Erosion Potential index models soil water storage relative to the [gamma] distribution of rainfall (Kirkby & Cox 1995). Te CSEP "provides a powerful and physically based methodology for estimating the climatic element in soil erosion" (Kirkby & Cox 1995: 351), but it also can be embedded in a more complete erosion model. The appeal of a simple physically based model, like the CSEP, is its applicability to a range of small map scales. At the coarse regional scale, "it is necessary to suppress topographic and soil detail, leaving only broad regional differences associated with lithology and climate" (Kirkby & Cox 1995: 334). As data for evaluating the CSEP increase in resolution, the model can be extended until it approaches the more complex modeling of soil and sediment yield at the scale of landforms and small watersheds.

Whereas hillslopes and channels are the framework for the modeling of fluvial geomorphic processes, geomorphologists generally have modeled wind erosion is the context of sand dunes and associated eolian landforms in contrast to wind erosion of agricultural soil. The scaling up from sand dunes, like slopes, also requires the use of primarily climate indices since in dune fields topography and thus exposure to wind vary over short distances. Wolfe (1997) demonstrated that the distributions of sand dunes on the Canadian plains could be modeled with a simple index of P/PE.

Models that predict soil loss from agricultural land have potentially practical application to a large part of the Canadian plains. Most of these models must first be calibrated or modified because they were not developed for the soil, climate and landscape conditions of the Canadian

plains where they have been used with limited success (Pennock & de Jong 1990). This has not prevented the estimation and publishing of soil loss rates with minimal understanding of the underlying physical processes, and even the publication of small scale maps, where the soil erosion risk for a large map unit simply represents the dominant or averaged degree of soil loss. The use of GIS and coupling of models with geo-referenced databases has facilitated the inappropriate use of models and data.

Whereas geomorphic models lack explicit practical application to managed landscapes, they are better suited to an evaluation of regional climate sensitivity of soil landscapes and the off-site impacts of erosion. Besides the on-farm impacts of reduced crop yield, soil loss also reflects climate sensitivity of a soil landscape at spatial and temporal scales beyond a farm or field and next year's crop. Whereas crops producers manage farms, institutions (governments) manage landscapes and have a mandate to ensure that agriculture and forestry are sustainable with a changed climate and landscape. Thus the modeling of climate impacts on soil landscapes necessarily must account for the regional risk and consequences of erosion.

5 A Practical Approach to the Assessment of Soil Landscape Sensitivity: Alternative to Process Modeling

Our review of existing models of soil loss and landscape change led to the conclusion that virtually all of them are inappropriate for a spatial analysis of the climatic forcing of surface processes in the Canadian plains. The greatest promise for a model-based approach to evaluating soil landscape sensitivity lies in relatively simple physically based models, because they are more scale robust than empirical models derived from the measurement of erosion from plots or than the intensive physically-based modelling of slope and channel processes. Appendix D describes the modeling and mapping of rainfall erosion risk in southwestern Saskatchewan using a model of Cumulative Soil Erosion Potential (CSEP), "a powerful and physically based methodology for estimating the climatic element in soil erosion" (Kirkby & Cox 1995: 351). The CSEP has relatively few and simple terms: threshold soil water storage, and two "empirical parameters that are fitted to the [gamma] distribution in the neighbourhood of a one year recurrence interval" (Kirkby & Cox 1995: 335-336). For practical purposes these terms are equivalent to hydraulic conductivity, the mean number of rain days per year, and mean rainfall per rain day. Because parent material (surficial geology) and synoptic climate have a regional distribution, CSEP can be modelled and mapped with relatively coarse spatial resolution. At some coarse scale, the model would fail to capture significant spatial variability in soil properties and rainfall characteristics. At finer scales, landforms can be resolved and the topographic control of erosion can be incorporated, as demonstrated in Appendix D. The appeal of a simple physically based model, like the CSEP, is its applicability to a range of small map scales. At the regional scale, "it is necessary to suppress topographic and soil detail, leaving only broad regional differences associated with lithology and climate" (Kirkby & Cox 1995: 334). As data for evaluating the CSEP increase in resolution, the model can be extended until it approaches the more complex modeling of soil and sediment yield at the scale of landforms and small watersheds.

A new generation of models simulate the interaction among spatial units (cells) of systems (Bak, 1996; Chase, 1992; Rodriguez-Iturbe and Rinaldo, 1997; de Boer, in press). These models apply to relatively coarse scale at which geographic expressions emerge that cannot be explained or modelled from the mechanics of processes operative at fine scales. Most of these models (*e.g.*, Chase 1992) simulate the fluvial landscapes that evolve from the growth of a network of stream channels. De Boer (in press) developed a cellular model that simulates the primary functional attribute of fluvial systems, the sediment dynamics that emerge at a watershed scale. While his model is entirely theoretical, it has major implications and potential application (see Results and Deliverables) to regional modeling the landscapes sensitivity on the Canadian plains, given the physical basis of the model and it coarse scale. Within many prairie landscapes, especially in disordered hummocky moraine, eroded soil is redistributed rather than exported to a stream (Ashmore & Day1988, Martz & de Jong 1991). Therefore only models of landscape evolution, and not soil loss equations, can account for sediment yields from prairie watersheds rates which are 2-3 order of magnitude below rate of erosion on cropland (Carson & Associates 1990).

Whereas mechanistic data-rich models are the ultimate research tool for prediction and understanding of complex systems, they tend to produce scientific knowledge that is not easily applied to the formulation of policy (Ingram, et al., 1996). The modeling component of adaptation planning either has to seem transparent to the planner or simplified to the essential or salient factors that capture much of the response to climate. For example, Ingram, *et al*. (1996) used a "reduced-form" of the EPIC model to evaluate the climate sensitivity of soil in the US Corn Belt and to demonstrate the highly non-linear variation in soil loss with rainfall and wind speed. Another practical alternative to complex mechanistic models is a qualitative expert system approach. Expert systems are another alternative to data-intensive process modeling. Since agrologists and farmers tend to know where and why erosion occurs on cropland, at least locally, their knowledge can be the basis for verifying the result of soil loss modeling (Harris and Boardman, 1990), in addition to data on stream sediment loads, topsoil depth and C-137 concentrations (Pennock *et al*., 1995).

Because soil landscapes respond to decreased resistance to wind and water or to an increase in the frequency and magnitude of hydroclimate events, the probability of climate-induced landscape change can be expressed as the ratio of resistance to disturbance (Brunsden and Thornes, 1979). A critical ratio of one represents a meta-stable landscape, sensitive to a change in climate that results in reduced surface cover or soil strength and /or more extreme hydroclimatic events. The most probable climate change scenarios for the Canadian Plains (see Appendix A) suggest a future landscape with lower resistance and also subject to higher disturbance. The forecasted higher mean temperatures, particularly in spring, will result in lesser soil moisture even with a modest increase in precipitation (Harrington, *et al*., 1997). As emphasized in section 1.1, land use will determine landscape sensitivity to future climate. Exposure of agricultural land to erosion will depend on whether climate favours expanded annual crop production or returning cropland to permanent cover. The first phase of our research was a review of "Climate Change Parameters and Scenarios as they Relate to Prairie Agriculture" and the corresponding soil landscapes. We (Frischke & Sauchyn) collaborated with the GIS Unit at PFRA (Harron & Nyirfa) to compile information on the climatic parameters that relate to landscape change and the land practices supported by the soil landscapes. This report is appended as Appendix A.

The least complex and most practical approach to evaluating landscape sensitivity is simply mapping regional indices that reflect, at a coarse scale, the controls on erosion on a local scale, (Table 1). Whereas the potential disturbance by water, wind and gravity can be expressed numerically, most of the resistance data, such as land use and soil texture, are categorical. Much empirical research would be required to convert soil and vegetation types to quantitative measures of resistance (e.g., shear strength, boundary layer roughness). Furthermore, agricultural land cover changes annually and seasonally. Some resistance terms can be expressed numerically because they are directly related to topography or climate, which are readily quantifiable. These include a measure of landscape disorder, the P/PE ratio, and persistent water deficit (drought) or surplus, which reduce resistance to surface erosion and landsliding, respectively. Some types of resistance cannot be evaluated from commonly mapped data because they reflect the geomorphic history of a soil landscapes (Brunsden 1993).

Dimensionless expressions of the topographic potential for mass wasting include slope gradient, the quotient of local and regional relief, or a composite index incorporating both gradient and relief. Because the southern Interior Plains are underlain by poorly-consolidated Quaternary sediments and Cretaceous bedrock, the potential for mass wasting occurs where the disturbance term is relatively high, that is, in the meltwater valleys, incised tributary valleys and uplands (Sauchyn, in press). Conversely, the distribution of potential wind erosion will reflect almost entirely the geography of resistance, as wind velocities exceed critical transport thresholds throughout the Prairie Ecozone (Muhs & Wolfe, in press). The ratio of precipitation to evapotranspiration (P/PE) is a good index of resistance, because it accounts for the distribution of both soil moisture and vegetation (Wolfe 1997). Cumulative wind energy or magnitude-frequency (Muhs and Maat 1993) is the basis for an index of the climatic potential for wind erosion (i.e., the disturbance factor). More specific climatic parameters include drift potential, the scalar sum of all winds capable of moving sand, and resultant drift potential, the vector sum of all sand-moving winds (Fryberger & Dean 1979).

Table 1. Local controls on erosion versus regional indices of soil landscape sensitivity

Local Controls	Regional Indices
rainfall intensity	daily rainfall
rainfall duration	annual storm
snowmelt rate	probable maximum precipitation
soil hydraulic conductivity	aridity index : P/PE
soil moisture content	soil water storage
wind velocity	peak stream flows
slope gradient	drainage density
slope length	slope length / relief
local relief	% wind > a critical threshold
plant cover	% of slopes > a critical threshold
soil texture	cumulative wind energy
infiltration rate	land cover / use

The ability to adapt and cope with climate change impacts is a function of wealth, scientific and technical knowledge, information, skills, infrastructure, institutions, and equity. (IPCC 2001: 63). Science is insufficient without mechanisms to apply it to decision making and in particular tools for the practical application of science. Towards this objective, we have implemented an Internet Map Server (IMS) at the PARC web site (www.parc.ca) for serving geographic data related to soil landscape sensitivity. The IMS is intended as a platform for sharing information and encouraging discussion of climate change impacts and adaptation. The map services are a geographic user interface for capturing time series data by location, for example, stream flow records by watershed. The IMS is a portal for the distribution of spatial data sets, such that a common spatial framework, such as ecological land classification, is in use throughout the PARC network of scientists and policy makers. A spatial data directory, including metadata files, facilitates the acquisition of georeferenced data via the PARC web site. The most advanced application of the IMS is the crude modeling of potential impacts of climate change. Researchers and stakeholders can apply simple climate change scenarios to geo-referenced biophysical and social data. With the IMS's limited capacity for spatial analysis, most geoprocessing and the climate impact modeling is done offline within a full-featured GIS environment. The IMS, however, is able serve the output from climate impact models, such that the model results can be customized by the web site user and be most readily applied to the discussion and analysis of adaptation strategies.

6 Results and Deliverables

Our PARC Quick-Start project has produced 1) a more thorough understanding of the conceptual and technical issues related to rigorous and spatially-explicit evaluation of the impacts of climate change on soil landscapes, and 2) a practical framework for enabling this evaluation and the planning of adaptation to minimize the impacts of soil landscape sensitivity on agriculture, forestry and water quality. The main deliverable is the interactive map services available at the PARC web site (www.parc.ca). The PARC IMS will be continuously updated as geo-referenced results of other PARC projects are delivered and as relevant geospatial data, that currently are proprietary and costly, are liberated by federal, provincial and municipal mapping agencies. There is trend in Canada towards lower relaxing user fees and license requirement for data compiled in the public sector. The current content of the PARC IMS represent data currently in the public domain (e.g., ecological land classification and soil landscapes of Canada) or inherited from PARC researchers. Most of these data are biophysical. Therefore, as the PARC IMS develops, a priority will be socio-economic data and map services.

Stemming from the current project are several research directions in pursuit of a scientifically rigorous approach to the planning of adaptation to impacts of climate change on soil landscapes. This further research includes:

1. M.Sc. thesis research (Joss; Appendix F) to identify the scale domains of commonly available digital topographic and land cover datasets. The focus will be on identifying spatial thresholds beyond which geographic data cannot be scaled up or down and retain physical meaning. Resolution, as a surrogate of scale, will be progressively coarsened

(aggregated) in an attempt to identify the effects of scaling-up upon the datasets. The spatial patterns produced at each stage of aggregation will be quantitatively analyzed in a geographic information system (GIS) and used to identify the upper threshold for each dataset's domain of scale. Growing awareness and concern over broad-scale issues such as global warming have emphasized the need to scale-up detailed knowledge acquired at fine scales. Much research in climate change impact assessment is concerned with the scaling down of climate change scenarios and the scaling up of local biophysical process data to the landscape level. This work requires, however, a better understanding of the scale thresholds beyond which geographic data do not retain their original meaning. Given the complexity and implications of scaling, there is a need for multi-scale analyses and the development of scaling theories. The application of these concepts permits identification of the limits to which information can be scaled.

2. M.Sc thesis research (Kennedy; Appendix E) on the derivation and use of synthetic soil landscapes for the assessment landscape sensitivity to climate change and variability. Synthetic landscapes can be derived from spatial and statistical relationships among the topographic, hydrographic, soil and geologic variables. Soil series, the basic classification unit used in soil mapping, capture spatial variations in parent material and local topography and drainage that result in differences in the properties of soil profiles. They are analogous to synthetic soil landscapes and components of them. The other component is the coarser-scale topographic and drainage, and aspects of geomorphic history, that govern the response of geomorphic systems to climate variability and hydroclimatic events. The concept of soil landscape as defined by soil scientists place the perspective on soil origin and productivity. A geomorphic perspective on soil landscapes requires a shift in emphasis from the pedon to landforms. These types of soil landscapes could be mapped from the synthesis and classification of geomorphic data. As a means of scaling up soil and geomorphic properties, this spatial synthesis would result in the best spatial data structure for the regional assessment of the climate sensitivity of soil landscapes. Synthetic landscapes are a basis for linking spatial scales as the synthetic data preserve, at a coarser scale, relationships among variables measured at a finer scale (Thorn, 1988).

3. Collaborative research to apply a cellular model of landscape evolution (de Boer, in press) to a real watershed in the Interior Plains. The model simulates the interaction among segments of the landscape (cells) that result in morphological and functional properties that "emerge" at a regional scale and cannot be predicted by local (slope and channel) processes and models. This approach to landscape modeling is very close in concept to the objective of evaluating of the regional sensitivity of soil landscapes. Sensitivities of soil landscapes to climate will be indicated by the adjustments to the physically-based model required to simulate the evolution of the morphology and sediment dynamics of an actual watershed.

4. Collaborative research on climate anomalies in relation to geomorphic thresholds. Whether sensitive landscapes are impacted by climate change will depend 1) whether major hydroclimate events occur at these locations and 2) when these disturbances occur. Landscape change occurs when and where antecedent conditions, either prolonged wetness or drought, have lowered resistance to a major hydroclimatic event. Thus, besides spatial modeling, another major aspect of the modeling of soil landscape sensitivity is the analysis of climatic variability in relation geomorphic thresholds. This analysis, arising from the project reported here, has taken in research in several directions:
    a. the frequency analysis of our dendroclimatic records for the southwestern prairies (Sauchyn and Beaudoin, 1998; Sauchyn and Skinner, 2001), specifically the probabilities of successive years of drought or abnormally high precipitation. These statistical data have value only with an understanding of the causes of and geomorphic responses climate anomalies (Klemes, 2000). Therefore, we also are
    b. the synoptic climatology of severe drought and prolonged wetness, by using modern analogues and by comparing air mass indices to our proxy climate records, and
    c. the modeling of soil-vegetation dynamics and the duration of drought required to induce phytoinstability and reduce surface cover below critical thresholds below which soils lose resistance to wind and water erosion. As emphasized above, land use of managed land (cropland) will determine climate impacts. Controls on land cover as a much different issue, although improved forecasting of climate variability and potential impacts on soil landscapes, could influence decisions about crops and cover. Whereas the current probabilities of severe erosional events ('once in a lifetime') mitigate discourage soil conservation, increasing probabilities would favour soil conservations or promote the retirement of marginal cropland.

Revisiting the project objectives, we sought to develop a methodology which was practical yet scientifically valid. Often it seems that these are conflicting aims, as science can be simplified until it has little meaning or practicality. For example, Klemes (2000) cited the widespread use of statistically forecasting in hydrology to satisfy the demands of engineers and planners. He demonstrated that the probabilities generated by these statistical methods can be meaningless or spurious in the context of the behavior of geophysical systems. The methodologies proposed here for spatial modeling of soil landscape sensitivity are practical, when applied via an IMS, however, the valid use of the geospatial data requires that we translate concepts like sensitivity, resistance, thresholds. This requires expressing abstract concepts in terms of measurable indicators of climate change impacts, as opposed to oversimplifying the problem of soil landscapes response to climate variability and change. Research arising from this project is focused on this goal, such that decision making about adaptation to climate change is based on methods and models that reflect the complexity of climate and biophysical systems.

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Appendix A: Climate Change Parameters and Scenarios as they Relate to Prairie Agriculture

Final Report to PFRA Geographical Information Systems Unit

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INTRODUCTION

> Since the settlement of the Prairies in the 19th and early 20th centuries, land use and farming practices have evolved to match the various climates and soil types on the Prairies and adapted to changing markets, technology and transportation systems. The abandonment of farms in the Special Areas of Alberta during the early 1920s, and southwestern Saskatchewan in the 1930s, provides evidence of these adjustment processes. More recently, since the 1980s, there has been a reduction in the summerfallow and an expansion of crop varieties, particularly in areas of higher moisture. (PFRA, 2000: 81)

This excerpt from the final report of the PFRA's Prairie Agricultural Landscapes (PAL) study captures the that, besides social and economic factors, the adaptation of agricultural systems to change is limited by soil, land form, vegetation and climate factors (Dumanski and Kirkwood 1988; Huffman *et al.*. 1993). The ecosystems and soil landscapes that support agriculture are diverse vary significantly over this large region, according to climate, landform and geological materials. Furthermore, they are periodically disturbed by the major hydroclimatic events (*e.g.*, intense rain and strong winds) that characterize the subhumid to semiarid Canadian plains. Prolonged dry or wet weather strongly influence the resistance of soil and vegetation to wind and runoff. In particular, prairie ecosystems and soil landscapes, and thus agricultural systems, are sensitive to year-to-year variability and longer-term fluctuations in the surface and shallow subsurface water balances (Lemmen and Vance, 1999). As a result, the sustainability of prairie agriculture depends on the adjustment of land use and management systems to climatic variability, the periodic fluctuation of atmospheric conditions (e.g., drought, early frosts, storms) and to climatic change, a significant departure from previous average conditions.

Prairie farming practices have historically been adapted to climatic variability to take maximum advantage of soil landscapes (Hill and Vaisey 1995). There is, however, a perpetual adjustment to weather and climate, and now the agricultural sector is faced with the prospect of climatic change, which may include climatic variability that exceeds the historic experience. Gullett and Skinner (1992) documented a statistically significant increase in temperature over the past century for the prairie provinces. The Canadian Climate Centre's general circulation model predicts that the largest CO2-induced rise in mean surface temperature in southern Canada will occur in the Interior Plains (Boer *et al.*. 1992). Most GCMs also forecast increased winter precipitation but with decreased net soil moisture and water resources in summer. Predictions of precipitation, however, are less certain than those for temperature (Herrington *et al.*., 1997).

The previously mentioned PAL study (PFRA 2000) identified unique relationships between farming practices and landscapes and the range of landscapes associated with a given set of agricultural activities. Certain landscapes and farming practices are more susceptible to change than others, whether the driver of change be economic, environmental or social. Whereas the PAL was driven current economic predictions and their potential impacts on prairie, the land practices groups could also be used as a basis for determining the impact of various climatic scenarios on economic and environmental conditions within these land practices groups. Therefore PFRA's Geographical Information Systems Unit has initiated a study that relates current knowledge and prediction of changing climatic parameters to the landscape and the land practices currently used on those landscapes. A better understanding of the sustainability of the current agricultural system can only be developed developing a landscape based approach to climate change.

The study will identify the landscapes and land practices that are most susceptible to changes in climate on the prairies and will suggest how the agricultural industry may respond to these scenarios. PFRA is determining the relevant climatic change scenarios and parameters in consultation with climate change researchers. This report is the result of consultation with researchers at the University of Regina. First we present a brief overview of two programs which classified Canada's landscapes according to capacity to support agriculture. The bulk of this report is a description and discussion of those climatic parameters and climatic change scenarios that most directly relate to prairie agriculture.

CLASSIFICATIONS OF SOIL LANDSCAPE CAPABILITY

Canada Land Inventory

The Canada Land Inventory (CLI) was completed in 1965 to provide "...a comprehensive survey of land capability and use designed to provide a basis for resource and land use planning" (Department of Regional Economic Expansion 1970). Land capability was determined for different uses including agriculture with emphasis more on land use planning than on land management. The spatial scale was only as fine as the municipal level; this inventory cannot be applied to smaller areas of land such as individual parcels and small watersheds.

The main parameters considered for the inventory of agricultural land uses were soil-related. Soil survey data were divided in seven classes of suitability for agricultural use. There were thirteen subclasses to further identify types of limitation. It was assumed that the soils were well-managed and cropped with mechanization prevalent. Organic soils, cultural patterns, type of ownership, skills of the operator, hazards of crop damage and location and size of farms were among those factors not included in this classification.

Land Suitability Rating System

This system was developed in the early 1990s after a number of concerns were raised about the CLI. The Land Suitability Rating System (LSRS) was a methodology for rating the suitability of land for spring-seeded small grains and primarily provides the land evaluation necessary for land use planning. However, there are other applications: agricultural assessment of disturbed/reclaimed lands, soil quality surveys, land productivity rating, and evaluation of crops other than spring-seeded small grains (Pettapiece 1995). The main limitation of the LSRS is restricting the assessment of land capability to sustainable arable agriculture, excluding the production of livestock or specific crops.

While the CLI was derived mostly from soil information, the LSRS is based on limiting land and environmental factors. Seven suitability classes are based on the degree of limitation of land for production of any given crop. There are many subclasses according to the type of limitation grouped into climate, soil and landscape factors. Under climatic factors, the main variables are moisture and heat/temperature. The climatic rating reflects the variable that is most limiting. The moisture index is the difference between potential evapotranspiration and precipitation (P-PE) and ranges from -150 mm (no moisture limitation) to -500 mm (severe moisture limitation). The temperature index, effective growing degree days, is calculated from growing season length, growing degree days and day length. The growing season is defined as beginning ten days after the average date of mean daily temperature of 5°C and ending on the average date of first frost after July 15. Growing degree days were adjusted to allow for longer day lengths in the north (Pettapiece 1995).

A few modifying factors are recognized as reducing climatic suitability. These regional factors include excess spring and fall moisture and fall frost. Excess spring moisture delays seeding and thus shortens the growing season. Too much moisture in the fall is also a problem as it interferes with harvest. The same (P-PE) index is used as the basic moisture factor. Fall frost is the occurrence of frost before the regional average date and is expressed as days before that average date. All of these factors have percentage deductions, which increase with the severity of the constraint on agricultural production (Pettapiece 1995).

CLIMATIC PARAMETERS

In 1997, the Prairie Farm Rehabilitation Association (PFRA) and the Canadian Institute for Climate Studies (CICS) hosted workshops in Winnipeg, Regina and Calgary concerning seasonal climate predictions and available products. A survey was conducted prior to the workshops to establish information needs regarding seasonal climate prediction. This rather informal survey captured most of the climatic parameters that are considered important in studies of climate change and agriculture. The twenty-five respondents, representing agriculture, water resource agencies, power utilities and other sectors, were asked to rate the importance of climate variables. All sectors rated precipitation as very important and temperature as important. Representatives of the agricultural industry rate the following parameters as very important by the: frost-free periods, growing degree days, number of rainfall event in September, and

occurrence of an open or closed spring or fall. They gave an important rating to seasonal moisture deficits, risk of pest infestation, date of last spring and first fall frosts, and the date air temperature remains above optimal growth temperatures (O'Brien 1997).

Temperature

Surface air temperature, likely the most important climatic factor, influences other aspects of climate such as evaporation, cloud cover, precipitation, length of growing season (Environment Canada 1995). Some of the impacts of an increased temperature include reduced risk of frost or low temperature stress on crops, increased evapotranspiration and risk of high temperature stress on crops; greater diversity of crops, but also weeds, insects and pests; increased probability of droughts and less winter stress on livestock (Ripley 1999). One of the most commonly used measures of temperature, or the thermal climate, is growing degree days (GDD), that is, the accumulative daily, monthly or annual temperature above a threshold temperature (Williams *et al*. 1987). Each plant species has a different minimum temperature restriction, but 5°C is most often used. Therefore, GDDs are a good indicator of the types of crops (and weeds) that will be affected by a climate change (Government of Alberta - www.agric.gov.ab.ca/agdex /000/7100001e.html).

The frost free period can be defined as the number of days from the average last spring date of below zero temperature to the average first fall date of the same conditions. Since most crops are severely affected by the incidence of frost, any change in the length of this period affects yield. The growing season length, the period during which crops can grow, is longer than the frost-free period. The start of the growing season can be defined as when five consecutive days of average daily temperatures reach 5°C. (Government of Alberta - www.agric.gov.ab.ca/agdex/ 000/7100001e.html).

Moisture

The moisture resources of the Prairies include precipitation, soil moisture and humidity (moisture in the air). Water vapour is also a greenhouse gas (Environment Canada 1995). Amount and type of precipitation largely determine the type of agriculture that an region can support. On the Prairies, frontal precipitation is associated from low pressure systems and convective precipitation from summer storms. Water on the Prairies is problematic when there is either too much or not enough. An excess of precipitation over a short period may cause flooding and/or soil erosion (Wheaton and Wittrock 1992b). Over a longer period of time (weeks, months), excess moisture can encourage insects and pests and greatly affect crop growth and yields (McGinn and Bootsma 1998). Too much surface water is frequently a problem in Manitoba (Dunlop and Shaykewich 1984). Lack of moisture can also affect pests and insects, but drought is the most serious potential problem. Soil erosion due to wind also becomes a problem under dry conditions (Wheaton and Wittrock 1992b).

According to the Canada Country Study (Herrington *et al*. 1997), information about the type, frequency, intensity and amount of precipitation is required before impacts of climate change can be understood. Williams *et al.* (1988) used a precipitation effectiveness index is based on monthly precipitation and mean temperatures. This index is useful for observing spatial patterns of a moisture regime. The Palmer Drought Severity Index (PDSI) is a measure of drought duration and frequency (Williams *et al.* 1988). It is expressed in terms of deviation from the normal climate and thus reflects both dry and wet spells. A drought represents as an extreme moisture deficit, when evapotranspiration exceeds precipitation to a large degree. In southern Saskatchewan and Alberta, mild summer moisture deficits exist much of the time (Wheaton and Wittrock 1992b). Soil moisture is related to drought and expressed in millimeters of equivalent precipitation deficit (Dunlop and Shaykewich 1984). Snowmelt water accounts for most of the spring soil moisture. Snow cover provides an insulating layer that not only helps to protect fall-seeded crops but also aids the survival of many insects and pests (McGinn and Bootsma 1998).

Evapotranspiration, the loss of water by the combined processes of evaporation and transpiration, is generally considered potential evapotranspiration. The LSRS used a measure of evapotranspiration in determining the moisture component of the rating system (Pettapiece 1995). Humidity, the moisture in the air, is expressed as 1) vapour pressure, the portion of air pressure caused by water molecules, 2) specific humidity, a volume independent ratio of the grams of water to kilograms of dry air, and 3 relative humidity, the percentage of actual to saturation humidity for a given temperature (Danielson *et al.* 1998).

Other Parameters

Besides temperature and moisture, radiation, wind and extreme weather strongly influence agricultural production. Solar radiation is a component of photosynthesis and affects evapotranspiration (Drennen and Kaiser 1998, Herrington *et al.* 1997, Wheaton and Wittrock 1992b). Cloud cover plays a direct role in the summer radiation balance. The Intergovernmental Panel on Climate Change (IPCC) estimated that cooling due to reflection of incoming radiation from clouds would exceed the warming due to reflection of outgoing radiation from clouds by approximately 25% (Environment Canada 1995). Cloud cover could increase with global warming as evaporation rates increase. Clouds alone are not an indicator of climate change, since the affect of cloud cover on climate (and vice versa) is a complex problem (Environment Canada 1995).

Wind and extreme weather are other aspects of climate change with implications for agriculture in terms of wind erosion, flooding and ecosystem stress and disturbance (Wheaton and Wittrock 1992b). Floods, droughts, severe storms, heat waves and other extreme weather reflect natural climate variability, but this variability could become exacerbated by climate change. Weather disasters may become more common (Francis and Hengeveld 1998, Hengeveld 2000).

CLIMATE CHANGE SCENARIOS

Types of Scenarios

The IPCC definition of climate change scenario is "...a plausible future climate that has been constructed for explicit use in determining the impacts of climate change on environmental and resource systems of importance to human society". There are two basic types: historical or areal analogues, and GCM-based or a hybrid (Wheaton 1990).
Historical scenarios are derived from archival information about an anomalous period or year to represent a possible future climate state. The advantage of these scenarios is that the responses to a particular change in climate are generally known and so they provide an indication as to what might happen in the future if a similar change in climate occurs. They are particularly useful for determining impacts on smaller regions. Wheaton and Wittrock (1992a) suggest the use of historical scenarios in conjunction with GCM-based scenarios. A limitation of historical scenarios is that the boundary conditions resulting in the observed climate of the year, or years, in question, may be quite different from those which will occur in the future and so a different climate response may be observed. Also, increases temperature observed over the historical period are generally less than those projected by global climate models, so the historical scenarios are useful only to examine possible changes in the very near future.

Factors to consider in the application of GCM-based scenarios include (Smith and Hulme 1998):

- Age of the GCM: More recent models generally perform better than older ones since they use the most up-to-date model physics and parameterizations, and improvements in computing hardware have meant that these models are generally of much higher resolution than earlier versions.
- Spatial resolution: The resolution of most GCMs is generally a lot less than desired and so selection of a GCM may depend on the resolution of the model.
- GCM validity: If a GCM is able to simulate the present climate reasonably well then more confidence is placed in its projections of future climate than would be given to a GCM which does not perform as well.
- Representativeness of the GCM results: By using the results from more than one GCM experiment, it is possible to obtain a range of values for a particular climate variable reflecting the uncertainty in the projections of future climate. For these reasons, Wheaton and Wittrock (1992a) and the IPCC suggest the use of more than one GCM-based scenario.

CCIS scenarios

Background

The Canadian Institute for Climate Studies (CICS) along with the Meteorological Service of Canada is leading an ongoing project entitled Canadian Climate Impacts Scenarios (CCIS) and funded by the Climate Change Action Fund. The purpose of this project is to provide climate change scenarios with Canadian relevance to impacts researchers. The scenarios constructed by the CCIS group are based on various but similar GCM experiments. The GCM experiments are

all warm-start; *i.e.,* the forcing due to greenhouse gases and aerosols over the historical period (generally mid-1800s to 1990) has been considered before initiating the climate change simulations. This permits an assessment of model performance over the observed period and also means that data for a model-simulated baseline period, corresponding to observed normal periods like 1961-1990, are available. In earlier transient GCM experiments, termed 'cold start', there was no representation of historical forcing and so a lag in model response to future forcing was observed due particularly to the thermal inertia of the oceans. This made it difficult to assign calendar dates to the model results. The CCIS website (www.cics.uvic.ca /scenarios/) provides scenarios for the three IPCC-recommended future time periods: the 2020s (2010-2039), the 2050s (2040-2069), and the 2080s (2070-2099). The scenarios are based on mean 30-year periods; in this way, the climate change signal is concentrated and the inter-decadal variability reduced.

CCIS provides output from CGCM1 from the Canadian Centre for Climate Modelling and Analysis, HadCM2 and HadCM3 from the UK Hadley Centre for Climate Prediction and Research, ECHAM4 from the German Climate Research Centre, GFDL-R15 from the US Geophysical Fluid Dynamics Laboratory, CSIRO-Mk2b from the Australian Commonwealth Scientific and Industrial Research Organization, NCAR-DOE from the National Centre for Atmospheric Research (data not available at time of publication) and CCSR-98 from the Japanese Centre for Climate System Research. Of significant interest to this study is the Canadian model, CGCM1 for which there is a large number of variables for which scenarios have been developed. This report includes information from the Hadley Centre experiments, only to show differences in predicted climate. The CGCM1 model has a spatial resolution of 3.75° latitude by 3.75°longitude, while the HadCM2 model has a grid of 2.5° by 3.75°. (CCIS - www.cics.uvic.ca/ scenarios/)

The Canadian GCM predicts maximum, minimum and mean temperature, precipitation, specific humidity, incident solar radiation, fractional cloud cover, wind speed, evaporation, soil moisture, mean sea level pressure, snow water content, sea ice, vapour pressure, relative humidity, potential evapotranspiration, diurnal temperature range and surface temperature. The Hadley Centre GCM also constructs scenarios for maximum, minimum and mean temperature, precipitation, fractional cloud cover and vapour pressure. Wind speed and a number of other variables are scheduled to be added. Of course, not all of these apply to this study (CCIS - www.cics. uvic.ca/scenarios/).

Aerosols affect climate directly by absorbing and scattering incoming solar radiation and indirectly by affecting the properties and longevity of clouds. Only sulphate aerosols are considered in climate change modeling. The main anthropogenic source is fossil fuel combustion, although these sulphate aerosols a limited atmospheric lifetime and are generally quickly rained out. The IPCC have recommended a number of greenhouse gas and sulphate aerosol emissions scenarios, including IS92a which is described as a "business as usual" forcing scenario. The GHG emissions associated with each scenario are converted into atmospheric concentrations and, in this way, their effect on the radiative balance of the atmosphere (the 'forcing') can be computed. Each emissions scenario uses different estimates of future population increases, future economic growth, and technology transfer. The IPCC has commissioned a new set of emissions scenarios, the Special Report on Emissions Scenarios

(SRES), which will be described in their Third Assessment Report (TAR) to be released in 2001. All of the forcing scenarios are considered to be equally likely, and the IPCC recommends that multiple scenarios be created and used in order to give an indication of the uncertainty associated with the projections of future climate (CCIS - www.cics.uvic.ca/scenarios/).

Ensemble-mean scenarios are also available for CGCM1 and HadCM2. These scenarios represent an approximation to the climate change signal, derived by simply averaging the individual experiments for these two models. The individual experiments differ only in their initial conditions, all future forcing *et cetera* is identical; thus giving an indication of the role of natural climate variability in the projections of future climate. The averaging process concentrates the climate change signal and damps the noise in the data due to natural climate variability. The CGCM1 model has three different experiments for greenhouse gases with aerosol (GA1, GA2, GA3), while the HadCM2 model has four experiments for both greenhouse gases with aerosol (GA1, GA2, GA3, GA4) and greenhouse gases alone (GG1, GG2, GG3, GG4). Ensemble-means are available for each group, labelled GAX and GGX Also available is one experiment for greenhouse gases alone under the CGCM1 model. Statistical confidence in the ensemble-mean would require a much larger number of experiments. However, since only three or four are available here, it is important to consider the ensemble-mean as an approximation. A more realistic scenario consists of the climate change signal plus noise related to natural variability, Thus at least one individual experiment should be considered alongside the ensemble mean. Ideally, several scenarios representing a range of future climate possibilities would be used in accordance with IPCC recommendations (CCIS - www.cics.uvic.ca/ scenarios/).

Baseline Climates

A proper baseline climate is an essential component of any climate change impact study. It provides for 1) a reference period to compare with future predicted changes, 2) testing of the validity of an experiment by running a simulation of the present climate, and 3) the identification of trends or cycles. The IPCC recommends that 1961-1990 is the best baseline climate period for most situations. Not only is this among the most recent data available, but it is also a relatively complete and reliable data set of climatological variables for most areas on earth (CCIS - www.cics.uvic.ca/scenarios/).

Climate normals for 1961-1990 are readily available for Canadian ecodistricts. Monthly data for such parameters as temperature (maximum, minimum and mean) and precipitation (rain, snow and total) were interpolated across the ecodistricts as defined by the Soil Landscapes of Canada. Also compiled are vapour pressure, wind speed, duration of bright sunshine, global solar radiation and dew point temperature. Several other variables were derived from other measures of climate such as growing degree days (for a number of threshold temperatures), effective growing degree days, growing season dates and length, potential evapotranspiration, water deficit, and precipitation surplus/deficit. All of these data are available from the CanSIS website (Agriculture and Agri-Food Canada - res.agr.ca/CANSIS/NSDB/ECOSTRAT/DISTRICT/climate.html 1997).

Scenario Results and discussion

The 2050s were chosen here for presenting climate change scenarios, because they represent the future, but not too distant. The data are annual and seasonal:. winter (December-February), spring (March-May), summer (June-August) and fall (September-November). All scenario data were derived from CCIS online database. The data presented in Tables 1-6 are average values for the grid cells that correspond to the prairie provinces. Differences in the predicted changes of mean temperature and precipitation are very noticeable among seasons, for both GCMs (Tables 1 & 2). The CGCM1 tends to predict larger mean temperature changes than the HadCM2. For precipitation, the CGCM1 tends towards less precipitation than the HadCM2, especially in the summer. In general, the CGCM1 is predicting a warmer, drier future climate than the HadCM2.

There are also differences between experiments that include aerosols (GAX) and those that do not (GG1 & GGX). The scenarios for mean temperature and precipitation reflect the earth surface cooling caused by aerosols. Mean temperature change is approximately 0.5° to 1.0° C less for the aerosol mean scenarios than for the greenhouse gas only scenarios.

Table 1. MEAN TEMPERATURE CHANGE (2050s) (^{o}C)

Time period	CGCM1 GAX Mean	CGCM1 GG1	HadCM2 GAX Mean	HadCM2 GGX Mean
annual	2.5 to 4.8	3.5 to 5.0	1.8 to 2.0	2.5 to 3.2
winter	3.0 to 6.0	4.5 to 6.8	3.0 to 3.5	2.0 to 4.5
spring	3.0 to 6.2	4.0 to 7.5	1.0 to 1.3	1.5 to 2.2
summer	2.2 to 3.2	3.0 to 3.5	1.0 to 1.8	2.2 to 2.5
fall	1.8 to 2.5	2.8 to 3.6	1.8 to 2.2	3.0 to 3.2

Table 2. PRECIPITATION CHANGE (2050s) (%)

Time period	CGCM1 GAX Mean	CGCM1 GG1	HadCM2 GAX Mean	HadCM2 GGX Mean
annual	0.0 to 10.0	0.0 to 10.0	5.0 to 18.0	7.0 to 15.0
winter	-3.0 to 6.0	0.0 to 13.0	13.0 to 25.0	10.0 to 25.0
spring	16.0 to 25.0	13.0 to 25.0	-3.0 to 25.0	15.0 to 25.0
summer	-14.0 to 3.0	-15.0 to 0.3	4.0 to 12.0	-4.0 to 5.0
fall	0.0 to 9.0	-0.2 to 15.0	7.0 to 25.0	5.0 to 17.0

Maximum daily temperatures are not projected to change as much as minimum daily temperatures in all scenarios from both models (Tables 3 & 4). Again, the cooling effect of aerosols is apparent and the changes are greater for the CGCM1 scenarios than for the HadCM2.

Such a change would essentially reduce the difference in temperature between day and night. Warmer nights and thus reduced incidence of frost would greatly affect many aspects of agriculture. Vapour pressure is presented as one of the available measures of humidity (Table 5). The same pattern of greater changes in the CGCM1 scenarios is seen here, as well as less projected change when aerosols are included. A wind speed change scenario is available only from the Canadian model (Table 6). On average, the projected changes are not large, but there are differences among the seasons. Spring, in particular, shows a great variety of change across the Prairies in both the greenhouse gas with aerosol scenario and the greenhouse gas only scenario.

Table 3. MAXIMUM TEMPERATURE CHANGE (^{o}C)

Time period	CGCM1 GAX Mean	CGCM1 GG1	HadCM2 GAX Mean	HadCM2 GGX Mean
annual	2.5 to 4.5	3.0 to 5.0	1.8	1.8 to 2.5
winter	1.5 to 5.5	2.0 to 5.2	2.0 to 3.0	1.5 to 4.0
spring	2.5 to 6.2	3.5 to 6.8	1.0	1.5 to 2.5
summer	2.0 to 3.5	2.5 to 4.3	1.0 to 2.0	2.0 to 3.0
fall	1.5 to 3.0	2.3 to 4.5	1.8 to 2.0	2.5 to 3.2

Table 4. MINIMUM TEMPERATURE CHANGE (^{o}C)

Time period	CGCM1 GAX Mean	CGCM1 GG1	HadCM2 GAX Mean	HadCM2 GGX Mean
annual	3.0 to 4.5	3.8 to 5.5	2.0 to 2.5	3.0 to 3.5
winter	5.0 to 7.0	4.5 to 8.5	2.8 to 4.2	2.5 to 5.5
spring	3.0 to 6.8	4.0 to 8.0	1.0 to 2.0	2.0 to 3.0
summer	2.8	3.5	1.5 to 2.0	2.5 to 3.5
fall	1.5 to 2.0	2.0 to 3.8	2.0 to 3.0	3.0 to 4.0

Table 5. VAPOUR PRESSURE CHANGE (hPa)

Time period	CGCM1 GAX Mean	CGCM1 GG1	HadCM2 GAX Mean	HadCM2 GGX Mean
annual	1.8 to 2.5	2.5 to 3.0	0.3 to 1.3	1.2 to 1.7
winter	1.0 to 1.5	1.3 to 1.8	0.6 to 1.0	0.7 to 1.2
spring	1.7 to 3.0	2.5 to 4.0	0.6 to 1.0	0.8 to 1.5
summer	2.6 to 3.3	3.2 to 4.0	1.3 to 1.7	1.5 to 2.3
fall	1.2 to 1.7	2.4 to 3.0	0.7 to 1.3	1.2 to 1.5

Table 6. WIND SPEED CHANGE (%)

Time period	CGCM1 GAX Mean	CGCM1 GG1
annual	-5.0 to 3.0	-8.0 to 0.3
winter	-10.0 to 0.0	-15.0 to 0.0
spring	-5.0 to 25.0	-5.0 to 20.0
summer	-10.0 to -6.0	-10.0 to 0.3
fall	-8.0 to -3.0	-13.0 to 0.3

Conclusion and Recommendations

We have several recommendations for the further study of climate change parameters and scenarios as they are related to prairie agriculture. The Canadian GCM model is recognized internationally as one of the best. It was used for climate change assessment by the U.S. National Academy of Science. The model climate predicted by the CGCM1 is quite stable, with little residual drift, and the mean global temperatures, sea level pressure patterns and atmospheric circulation simulations are realistic. Also, the general characteristics of the present climate are modeled well (Hengeveld 2000).

1961-1990 is the recommended climate baseline. Data are readily available for many climatic parameters for Canadian ecodistricts. The various CGCM1 scenarios and the ecodistrict climate normals for 1961-1990 use a similar set of climatic variables. These variables must be defined and computed in the same way for both the baseline and the future climate. The LSRS can then be used to evaluate the land under a changed climate using the predicted climate variables. Table 7 shows a comparison of the climatic parameters available from the climate normals database, the Canadian GCM model results and the LSRS.

Table 7. COMPARISON OF RELEVANT CLIMATIC PARAMETERS

CLIMATIC PARAMETER	CLIMATE NORMALS DATABASE 1961-90	CGCM1 VARIABLES FOR FUTURE CLIMATE	LSRS VARIABLES
Temperature	average daily mean (^oC)	mean daily (^oC)	
	average daily maximum(^oC)	maximum daily(^oC)	
	average daily minimum (^oC)	minimum daily (^oC)	
	mean hourly dewpoint temperature (^oC)		
	growing degree days above 0^oC, 5 ^oC, 10 ^oC & 15 ^oC		included in calculation for EGDD
	growing season start & end (calendar date)		included in calculation for EGDD
	growing season length (days)		included in calculation for EGDD
	effective growing degree days		effective growing degree days modifying factor: days before fall frost
Moisture	precipitation: rain (mm), snow (cm) & total (mm)	precipitation: total (% change)	
			moisture factor: (P-PE) index excess spring & fall moisture: (P-PE) index
	mean hourly vapour pressure (kPa)	vapour pressure approximation (hPa)	
Others	duration of bright sunshine (hours)		
	mean hourly wind speed (km/hr)	wind speed (% change)	

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Appendix B: Sensitivity of Soil Landscapes to Climate: The Theoretical Foundation

Dave Sauchyn

Scientific philosophy dictates that "it is impossible to do anything more than trivial work without some theoretical context" (Kirkby, 1990: p. 64). Abstract thoughts about landscapes range from unconscious preconceptions to models deduced from physical principles. The complex and non-linear (threshold) behaviour of geomorphic systems is described by a body of concepts that serve as a theory of geomorphic response to climatic change and variability (Thornes and Brunsden, 1977; Brunsden and Thornes, 1979; Schumm, 1975, 1977, 1981; Brunsden, 1990, 1993; Bull, 1991).

The study of climatic change impacts on soil landscapes requires a shift among earth scientists from the measurement and modeling of slope and channel processes to the coarser scale of global climate change and the impacts of human activities (Thomas and Allison, 1993; Jones, 1993; Vitek and Giardino, 1993). The primary evidence for the reconstruction of landscape history is fragmentary, discontinuous and possibly unrepresentative sedimentary deposits (Clayton, 1983). Whereas paleosols are the geologic record of "stable" landscapes, lithostratigraphy represents the periodic response of geomorphic systems to climatic change, extreme hydroclimatic events, intrinsic thresholds, and/or lowered resistance. The timing and duration of this response can be out of phase with the climate associated with the process domain, while the disequilibrium propagates through the geomorphic system. For example, glacial deposits, landforms, and tectonic structures have a prolonged influence on the apparent geomorphic response to postglacial climates (Church and Ryder, 1972; Matheson and Thomson, 1973; Sauer, 1978; Church and Slaymaker, 1989).

The inference of climatic forcing of geomorphic process from sediments and sedimentary structures requires a convergence of methodologies, which have historically segregated the earth sciences, despite a common goal of reconstructing process and landscape. "The very nature of landscapes requires geomorphology to assume the dual nature of being both a historical and physical science" (Ritter, 1988: p. 160). Process geomorphology is based on the explanation of landform and sediment yield in terms of process mechanics, the concept of the geomorphic system, and the time-independence of geomorphic activity, as a function of spatial variation in controls and resistance and the mutual adjustment of process and form. In contrast, studies of landscape evolution are naturally historical with the emphasis on stratigraphy, chronology (time-dependence), age-correlation of lithofacies, and reconstruction of sedimentary environments.

A geomorphic response to climate consists of reaction time, the interval between a hydroclimate disturbance or change in controls and observable morphological change, plus relaxation time, the ensuing period of adjustment up to a new equilibrium or another threshold (Bull, 1991). Whereas climatic change tends to produce a regional response and ultimately shifts in process domains, hydroclimatic events (climatic variability) and internal perturbations (intrinsic thresholds) generally are more difficult to recognize or verify. Rather than a response to climatic forcing, erosion and sedimentation can represent the self-regulation of a geomorphic system (dynamic equilibrium), with exponentially decreasing activity after a period of more rapid

adjustment, typically involving negative feedback (Welch, 1970; Thornes and Brunsden, 1977). A key variable in the reconstruction of geomorphic history is the length of relaxation relative to the periodicity of disturbances or changes in controls, which exceed thresholds (Wolman and Gerson, 1978). High-magnitude, low-frequency events tend to be over represented both stratigraphically and morphologically, because the outcomes are persistent, unlike the typically more subtle imprints of quasi-continuous erosion and sediment transport, even though these processes may have a greater product of magnitude and frequency.

The response of soil landscapes to hydroclimatic events depends largely on resistance as a function of surficial geology, geomorphic history, and the climatic control of vegetation and sub-surface water. Differential geomorphic activity commonly reflects the distribution of resistance and available sediment, or the unique histories of geomorphic systems, rather than spatial variation in the efficacy of climate as a geomorphic agent. Where resistance is lacking, deposits are reworked and landforms modified, and the stratigraphic record can be biased towards more recent events (Clayton, 1983). Unusually thick sequences of sediment can represent a local lack of resistance or an atypical depositional environment (*e.g.* buried valleys). These sections attract the Quaternary geologist, in the same way that process geomorphologists instrument the most active, but often anomalous, landforms.

Most landscapes also include elements that resist change, by virtue of geological properties (strength resistance) and/or previous evolution to a stable form (filter and system-state resistance; Brunsden, 1993). An example from the Canadian plains is the mid-Holocene accumulation of loess, which initiated a period of reduced erosion, because infiltration rates were higher in the loess than in the underlying Cretaceous shales (Bryan, *et al.,* 1987). Structural resistance to landscape change includes disorder in hydrologic and geomorphic systems, which is generally characteristic where the climate inherits a landscape that is the product of glaciation.

Understanding of the climatic forcing of landscape change behaviour of geomorphic systems is relative to scales of space and time. Relationships among controls and responses, and types of equilibrium, differ among cyclic (geologic), graded, and steady (engineering) time (Schumm and Lichty, 1965; Thornes and Brunsden, 1977: p. 15). Processes operating at one spatial scale can predispose a landscape to processes of different magnitudes and frequencies operating at another scale (deBoer, 1992). In the Alberta badlands, for example, geomorphic thresholds are scale-dependent, such that the controls on sediment yield from basins are not evident or relevant at the scale of slopes (deBoer and Campbell, 1989). This implies that the inference of process from sedimentary records also requires recognition of type and degree of coupling (structural resistance) between parts of a geomorphic system: slopes, channels and sediment sinks and, in general, discontinuous sedimentary deposits and the erosional history of source areas (Schumm, 1981). Disturbance of geomorphic systems tends to result in complex sequences of erosional and depositional events, such that, the response of adjacent channels, slopes or even cross-sections can be expressed at different rates, and even at different times. This complex response (Schumm and Parker, 1973; Womack and Schumm, 1977) is an aspect of filter resistance (Brunsden, 1993), causing changes in rates of erosion and sedimentation independent of climatic variation.

Key Concepts

Magnitude and Frequency

- how often an event of a certain magnitude occurs expressed as
    - the number of occurrences relative to a period of time or number of observations
    - the probability of such an event, or
    - the recurrence interval (return period)
- magnitude and frequency are inversely related
- lognormal frequency distributions are common, because the lowest magnitude is fixed at just above zero but the upper magnitude (rare events) is limited only by earth and atmospheric physics

Wolman and Miller (1960) determined that at least 50% of sediment transport was by flows of a magnitude that occurred at least once per year, that is, that events of intermediate magnitude and frequency generally dominate fluvial sediment transport. This benchmark analysis sparked much further consideration of magnitude and frequency including elaboration of the concepts and recognition of its limitations and complexities:

1. the common calculation of recurrence intervals for meteorological and hydrological events is useful but the geomorphic significance of these events also depends on other controls (*i.e.* vegetation, soil, morphology and rock)
2. frequency and magnitude assume stationarity of the series, that the mean and variance do not vary over time (basically equivalent to substantive uniformitarianism), however trend, persistence and intermittency in the behaviour of geomorphic systems makes the frequency distribution an incomplete description of a sequence of geomorphic events
    - trend, the direction of change, can include cyclic patterns
    - persistence (autocorrelation) occurs when a value influences an adjoining value in a series (*e.g.* tree ring widths) and implies that the true variability of a series may not be evident in a short record
    - intermittency, the nonperiodic clustering of similar values over long periods, is perhaps the most problematic because cumulative effects can have large geomorphic impact
3. extremely rare events (*e.g.*, once in half a million years or an annual probability of 10^{-5}) may have tremendous geomorphic consequences as postulated by neocatastrophists (*e.g.* draining of glacial Lake Missoula creating the eastern Washington scablands)
4. there is a fundamental difference between the processes of quasi-continuous sediment transport and the processes that create landforms in terms of magnitude/ frequency characteristics
    - therefore the effectiveness of geomorphic events can be expressed in terms of timing and magnitude relative to other events and the recovery (relaxation) of the geomorphic system
    - if two low frequency events occur in consecutive years, they will differ in effectiveness as the landscape will be rendered more (*e.g.*, lag deposit) or less resistant (*e.g.*, lack of vegetation) by the first event
5. just as magnitude and frequency relationships differ between transport and formative processes, they also differ for various parts of a landscape, particularly between stream

channels and interfluves, and over larger areas between regional climates (note: the original magnitude/ frequency work was based in humid temperate climates)

6. for the above reasons, comparisons of the effectiveness of various geomorphic processes are increasingly based, not on magnitude and frequency, but on more uniform measures of erosion such as mass of sediment moved or amounts of geomorphic work

Reaction and Relaxation

- absorbing and adjusting to change or disturbance, respectively
- disturbances or changes in controls, that exceed geomorphic thresholds, can be classified as either
    - pulsed: short duration compared to time period under consideration (*e.g.,* tectonism), or
    - ramped: sustained at a new level once initiated (*e.g.,* climatic change)
- the response of a landscape in quasi-equilibrium is to absorb the input without changes
- the response of landscapes and geomorphic systems often occurs over longer time periods than the duration of the disturbance or change in controls (inputs)
  reaction time: the interval between a disturbance or change in controls and observable morphological change
  relaxation time: the ensuing period of adjustment up to a new equilibrium or another geomorphic threshold

Hysteresis

- incomplete reversibility (Gr. a deficiency, same root as hysteria)
- when a condition changes from A to B and back to A, the pathways may differ and thus condition a may not be regained
- *e.g.*, soil moisture or suspended sediment load before and after a storm
- this usually results from a change in boundary conditions caused by the process (*e.g.*, residual stress from loading and unloading of clay)

Equilibrium

1. stable: tendency to revert to a previous condition after a limited disturbance
2. unstable: a small disturbance results in continuous movement away from an old equilibrium and towards a new stable one
3. metastable: an incremental change (trigger mechanism) pushes a system across a threshold from stable equilibrium to a new equilibrium
4. steady state: numerous small-scale about a mean that has no trend
5. dynamic: balanced fluctuations about a trending, nonrepetative mean value; often called quasi-equilibrium because of the tendency towards a steady state with a trending mean (*i.e.*, equilibrium is never attained)
6. dynamic metastable: both dynamic and metastable, fluctuations about a trending mean interspersed by large jumps as thresholds are crossed; used by many geomorphologists to explain landscape behaviour

- the concept of entropy, the degree of disorder in an isolated system, and the second law of thermodynamics dictate that, irrespective of the initial level of energy, energy becomes more evenly distributed over time (*i.e.*, energy gradients are reduced) and processes proceed at an ever decreasing rate
- the state of equilibrium is the most probable energy distribution, that is, uniform with least work (least landscape change)
- equilibrium explain characteristic (least-work, graded) landforms like longitudinal stream profiles, stream channel meanders, dendritic drainage networks, and concave-convex slope profiles
- there is rapid change away from any highly abnormal configuration of a system, corresponding to the notion of initially rapid change in response to an input or disturbance and then a decreasing rate of change over time
- a tendency toward equilibrium is favoured by a variety of reaction and relaxation times, and a constant stream of inputs which all but preclude equilibrium
- equilibrium is relative to the timescale of interest; a landform can be in equilibrium with respect to one timescale (graded or steady) and in disequilibrium with respect to another (cyclic)

Feedback

- accounts for movement away from (positive) and back to negative)a mean value
- that is, the effect of a disturbance or change in controls is either magnified or dampened, respectively

Threshold

- a transition in behaviour, operation or state
- a large response to a small or incremental change
- extrinsic and intrinsic, *i.e.*, response to change in an external (*e.g.*, climate) or internal (*e.g.*, shear strength) variable, respectively

Complex response

- parts of a geomorphic system approach equilibrium at different rates and a single part will exhibit different tendencies at different times
- difficult to recognize from short term process studies
- serious implications for interpretations of earth history, by precluding the interpretation of single causes for geomorphic responses identified in the quaternary record
- *e.g.*, the incision of One Tree Creek, Alberta, and formation of terraces, was the response to both base level change as the Red Deer River shifted across its floodplain and to Holocene climatic changes; the first factor is imposed from the mouth of stream the second controls the supply of water and sediment to the channel from upstream
- implies that earth scientists need to be much more rigorous and precise in defining their temporal and spatial scales

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Appendix C: Modeling the Hydroclimatic Disturbance of Soil Landscapes on the Canadian Plains: The Problems of Scale and Place

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Abstract: The sensitivity of soil landscapes to climatic variability and hydroclimatic events can be expressed as a landscape change safety factor, the ratio of potential disturbance to resistance to change. The use of a geographic information system (GIS) enables the spatially-explicit modeling of landscape sensitivity, but also raises the risk of violating the characteristic scales of disturbance and resistance, because the GIS technically simplifies the extrapolation of models, and associated concepts, to landscapes and scales not represented by the digital data base. Embedding landscape sensitivity into hierarchy theory, the formal analysis of the hierarchical structure of complex systems, provides a conceptual framework for the transfer of models and variables among landscape scales.

In the subhumid southern Canadian plains, major hydroclimatic events (strong winds, intense rain, rapid snow melt) cause much of the physical disturbance of soil landscapes and terrestrial ecosystems. Prolonged dry or wet weather influences the resistance of soil and vegetation to these events. The potential disturbance of soil landscapes therefore can be derived from the probabilities of extreme events and seasonal conditions, as recorded in instrumental and proxy climate records. This time series analysis can be linked to the modeling of landscape sensitivity by establishing the probabilities of hydroclimatic events and climatic conditions which may exceed or lower the resistance of individual soil landscapes.

Keywords: disturbance, GIS, geomorphology, landscape sensitivity, modeling

1. Introduction

The sensitivity of subhumid landscapes to climate change and hydroclimatic events (Bull, 1991), and forecasts of global warming, necessitate the study of the southern Canadian plains for the impacts of climate on biophysical processes (Herrington *et al*., 1997; Lemmen and Vance, 1999). The Canadian Climate Centre's general circulation model predicts that the largest CO_2-induced rise in mean surface temperature in southern Canada will occur in the Interior Plains (Boer *et al*., 1992; Laprise *et al*., 1998). Recent projections forecast net average warming of 4–6° C by 2050 AD (Government of Canada, 1997). Most models also forecast increased average winter precipitation but with decreased soil and surface water in summer.

Climatic change research challenges earth scientists and ecologists to apply their understanding of biophysical processes measured over small areas (plots, slopes, stands, *etc*.) to the modeling of processes at a landscape scale (Running *et al*., 1989; Sugden *et al*., 1997; Vitek and Giardino, 1993). Studies of climate impacts can be categorized according to the degree to which place, scale and spatial heterogeneity are recognized:

1. spatially implicit: forecasting change to biophysical systems without specific reference to location, *e.g.,* impact of climate change on the boreal forest
2. spatially discontinuous: evaluating models at points and interpolating among these locations, *e.g*., climate stations or grid intersections
3. spatially continuous: evaluating a model (*e.g*., soil erosion risk) by map unit
4. spatially continuous and explicit: modeling the spatial distributions of specific variables, *e.g*., the spatial distributions of disturbance and resistance

The fourth approach is enabled with a geographic information system (GIS), as described here for the mixed grass prairie ecoregion of the southern Canadian plains (Figure 1). Use of a GIS and digital geographic data also raise the potential for misuse of models and data, because a GIS technically facilitates and simplifies the extrapolation of models, and associated concepts, to landscapes and scales not represented by the digital data base. A review of existing models of landscape change leads to the conclusion that virtually all of them are inappropriate for a spatial analysis of the climatic forcing of surface processes in the Canadian plains (Sauchyn, 1997, in press). This region lacks the geomorphic and hydrologic characteristics that most models assume. More important is the lack of a theoretical basis for the modeling of process or disturbance over large areas, in this case 138600 km^2. Therefore this paper first examines the problems of place and scale, and then applies the concepts of landscape sensitivity and hierarchy theory towards a framework for the regional modeling of climate impacts on natural systems, and in particular the hydroclimatic disturbance of soil landscapes.

2. The Problem of Place

Place is an important consideration because most any large area has a unique combination of biophysical characteristics that often prevent the legitimate use of models derived elsewhere, and with increasing space and geographic diversity, prediction and verification become less feasible (Church, 1996; Haff, 1996). Use of analogues, a common approach to climate impact assessment, is problematic without complete understanding of the physical geography and

geologic histories of the comparative regions. For example, the present climate of the southern Great Plains is a tempting analogue for the future climate of the northern Great Plains. Despite the appeal to substituting the regional climatic gradient for climatic change over time, the northern Great Plains lie within the limit of late-Pleistocene glaciation and therefore have very different regional morphology, hydrography, soils and biogeography. Similarly, intervals of Holocene aridity (*e.g.*, the hypsithermal and medieval warm periods) could be poor analogues for global warming, if the current human impacts on the atmosphere cause the global climate system to shift to a brand new state (Broecker, 1994).

For the purpose of the spatial modeling of climate impacts, a digital geographic database was constructed for the mixed grass prairie ecoregion of the southern Canadian plains (Figure 1; Sauchyn, 1997), the region commonly known as Palliser's Triangle. Following his expedition of 1857-60, Captain John Palliser concluded that this region was "by no means a desirable district for settlement." and that a large area "will for ever be comparatively useless" (Palliser, 1859: 9). Nevertheless, EuroCanadians settled Palliser's Triangle and converted it to agricultural land use, but not without major and continuous adaptations to climatic variability, especially seasonal shortages of water. In this subhumid to semi-arid region, major hydroclimatic events (strong winds, intense rain, rapid snow melt) and prolonged drought have a profound impact on soils and vegetation. Much of the change in ecosystems and soil landscapes is driven by the surface and shallow subsurface water balances (Lemmen and Vance, 1999).

Late-Pleistocene glaciation of an interior sedimentary basin created a landscape in the Canadian plains which differs significantly from the boundary conditions assumed by most models of the climatic forcing of geomorphic processes (*c.f.*, Kirkby, 1993; Willgoose *et al.*, 1992). With a short geomorphic history and dry climate, the landscape is poorly integrated and the sediment budgets of slopes and channels are mostly unrelated or "decoupled" (Phillips, 1995). Water erosion mostly redistributes soil locally, especially in the extensive areas of hummocky and rolling moraine (Pennock and de Jong, 1995). There are few permanent streams. Large areas are internally drained by intermittent stream flow into shallow saline lakes. Lacking are the order and characteristic structure of a landscape dissected by an integrated stream network (Lemmen *et al.*, 1998), except over small areas which have evolved rapidly since deglaciation. At a regional scale, these small areas are segments of larger landscapes. For example, badlands are scattered throughout the valley networks. Among the geographic characteristics of the mixed grass prairie ecoregion (Table 1), its area (138600 km^2) necessitates modeling of climate impacts at a coarse-scale.

A suitable spatial data structure for modeling geomorphic systems at coarse scales is largely a practical consideration (Running *et al.*, 1989; Sauchyn, 1997), because the sources of geo-referenced data covering large areas are digital satellite data and existing small scale maps. The geographic expressions of geomorphic processes, landforms, are not mapped systematically over large areas. The mapping of Quaternary or surficial geology, at least in Canada, tends to be at relatively small map scales given the size of the country. Also classification schemes can vary among mapping agencies. For the small proportion of Canada which is arable land, soil surveys are generally available at relatively large map scales and with a consistent legend (Expert Committee on Soil Survey, 1987). Most soil maps capture landforms, because topography is a primary control on soil formation and geography at larger map scales. Given the relevance and

scale of these soil surveys, the soil landscape and soil landscape map unit are the most useful concept and construct, respectively, for the modeling of the sensitivity of geomorphic systems to climate. Soil landscape is a key concept in the field of soil geography (Buol et al., 1980; Hole, 1978). In a textbook devoted to "the study of the soil landscape from a geographic perspective (p. xv)", Hole and Campbell (1985) concluded from a literature review "that soil landscape, and the abbreviation soilscape, are of value as general introductory terms, but perhaps not as specific ones" (p. 12). Accordingly, they used a broad definition: "the total mass of unconsolidated geologic and pedologic material ". Applying this concept to soil survey, however, requires an operational definition: "The full array of attributes that describe a distinct type of soil and its associated characteristics, such as landform, slope, water table, permafrost and lakes, is called a soil landscape" (Shields *et al*,, 1991: 5).

3. The Problem of Scale

> "It has thus been generally agreed (although not always observed in practice) that different processes become significant to our understanding of spatial patterns at different scales. For the most part, however, we have no measure of the scale at which a particular process has most to contribute to the formation of a spatial pattern and our notions regarding the scale problem remain intuitively rather than empirically based." (Harvey, 1968: 71-72)

Harvey's discussion of the "scale problem" was published at the very early stage of a technical revolution in the geographical sciences: satellite remote sensing and geographic information systems have enabled the empirical analysis of geographic patterns at regional to global scales. At the same time, the rigorous observation and measurement of processes has focused much geomorphic and ecological research on human scales of time and space where natural phenomena are most accessible (Hoekstra *et al*., 1991; Saab, 1999; Vitek and Giardino, 1993). Typical sampling frames include the stand and plot in ecology; slopes, channels, and small catchments in hydrology and geomorphology; and catenas in soil science. A "scaling down" of climate and a "scaling up" of process is required to link the modeling of climate at coarse scales to biophysical processes at finer scales (Bass, et al., 1996; Hostetler, 1994; Kirkby et al., 1996; Sugden *et al*., 1997). Schumm's (1991: 38) suggested that "earth scientists operate at the wrong scale for the problems that they are required to solve ... records are too short as our scientific lives. Perhaps the present is too short to be a key to the past or future." The study of geomorphic and ecological processes also has tended to be at the wrong spatial scale to address regional and global problems.

While coarse observations of large areas cannot explain the climate forcing of most biophysical processes, the decades of detailed observation and experiments have led ecologists and earth scientists to recognize that this methodology can produce poor judgements about larger areas and times spans (Spedding, 1997). Most process simulation models fail to work when scaled up because of the greater complexity of larger systems and non-linearity caused by feedback among system variables, and the emergence of characteristic patterns and processes at coarser scales (Haff, 1996). The most serious violations of scale involve the application of empirical plot-scale models to remote locations and / or regional scales. Agricultural soil loss commonly is predicted by extrapolating empirical equations, notably versions of the Universal Soil Loss Equation

(Wischmeier & Smith 1978), sometimes over large areas (e.g., Logan et al. 1982; Snell 1985). This requires judicious interpretation of the soil loss predictions, because parameter values averaged over heterogeneous map units represent a misuse of these empirical field-scale models (Wischmeier, 1976; Roels, 1985; Sauchyn, 1993).

Another violation of scale involves the evaluation of process models at high resolution and then aggregation of the results over large areas with low resolution. This patching together of simple small-area models to account for the behaviour of complex systems is inappropriate because the relevant and dominant variables change with scale (Klemes, 1983; Schumm, 1991). Thus, for example, the understanding of ecosystems is not based on the individual behaviour of organisms (Saab, 1999; Valentine, and May, 1996). Stream slope is correlated with the size of bed materials over short distances and with discharge (climate) over longer reaches. Local vegetation and soil reflect topography and drainage, the controls with the strongest local gradients. The regional distributions of soil and vegetation reflect mostly synoptic-scale climate and historical biogeography.

The geographical tradition of mapping regional climate from vegetation associations and zonal soils assumes a stable climate, whereas "the earth climate system has proven beyond any doubt that it is capable of jumping abruptly from one state of operation to another." (Broecker, 1997: 1). Long system relaxation times following perturbations and persistence of the effects of major disturbances cause lack of agreement between contemporary patterns and boundary conditions. Scaling up in time and space gives historical and geographic context to local observations. The streams of the southern Canadian plains, for example, mostly flow in large valleys which were created at the margins of an ice sheet or from the draining of glacial lakes, and commonly do not conform the regional topographic gradient. The geometry of the stream channels tend to conform to the time-independent principles of stream hydraulics. This is another example of how explanation of form changes with scale, in this case as past processes become evident at a coarser scale.

A scientific community previously preoccupied with the detailed observation of small areas is now emphatic about the significance of scale:

> “it is, I will argue, the fundamental conceptual problem in ecology, if not in all of science. Theoretical ecology, and theoretical science more generally, relates processes that occur on different scales of time, space and organizational complexity. Understanding patterns in terms of the processes that produce them is the essence of science, and is the key to the development of principles for management.” (Levin, 1992: 1944)

> "Because science hopes to enhance understanding, necessarily in human terms, it may not be bad that ecology is scaled in human terms. Rather than fight human nature, ecologists are well advised to be explicit about the scales they use, so that they can anticipate the consequences of decisions that were formerly made subconsciously. By modeling with appropriately scaled concepts, ecologists can hope to advance with fewer delusions of objectivity, but more consensus." (Hoekstra, et al., 1991: 154)

These statements reflect a new or renewed interest in scale among ecologists. Geomorphologists, with their geographic roots, periodically remind themselves of the fundamental significance of scale:

> "it is possible to argue that, to date, geomorphologists have considered that the difficulties associated with widely varying scales of enquiry constitute a strait jacket for the subject: in reality, however, these problems may point to the fundamental skeleton of the discipline. If we understood the nature of that skeleton more clearly then we might also understand the rules linking events and forms on different temporal and spatial scales. (Kennedy, 1977: 156)

> "Spatial analysis should assume a greater role in geomorphology and hydrology, in at least two ways: determination of the scale of spatial patterns, and identification of scale-related breaks or discontinuities in relationships." (Phillips, 1988: 311)

> "we arrive at the possibility to ground theories of landscape (and, I would claim, of all else) in some concept of order at various distinct scales. This is what humans seek." (Church, 1996: 168)

The shared histories of the "composite" natural sciences (Drury and Nisbet, 1971; Osterkamp and Huff, 1996) have evolved to a mutual use of scale to reconcile equilibrium (time-independent) and developmental (time-dependent) philosophies (Church, 1996), but they have yet to produce a theoretical basis for the transfer of observations and models among scales. The hierarchical classification of soil and ecological map units (Hole and Campbell, 1985; Wiken, 1986), and the spatial resolutions of earth observation satellites (Running, et al., 1989), are pragmatic solutions to the problem of recording and mapping the spatial expressions of biophysical processes operating over various time scales. Sediment budgets and biogeochemical cycles are a dynamic basis for scaling in geomorphology and ecology, but lack the universality and continuity of atmospheric and oceanic circulation and the hydrological cycle that are the basis for physically-based scaling of climate and hydrologic systems (Bass, et al., 1996; Hostetler, and Giorgi, 1993; Klemes, 1983). The scaling of biophysical systems requires a conceptual framework which preserves the "spatiotemporal integrity and characteristic scale" (Valentine and May, 1996: 23) of system variables, and accounts for the change in relevant and dominant controls and responses with spatial and temporal scale.

4. Landscape sensitivity and hierarchy theory

A methodology for identifying combinations of surficial material, landform and land cover that may respond to climatic variability and change (Sauchyn, 1997, in press) was built initially on the concept of landscape sensitivity, "the likelihood that a given change in the controls of a system will produce a sensible, recognizable and persistent response" (Brunsden and Thornes, 1979: 476). The probability of a geomorphic response can be modeled and mapped as a landscape change safety factor: "the ratio of the magnitude of barriers to change [resistance] to the magnitude of the disturbing forces" (Brunsden and Thornes 1979: 476). A continuum of landscape sensitivity can be derived from the relative spatial distributions of disturbance and

resistance variables, such as the probabilities of hydroclimatic events, clusters of events, and seasonal and annual climatic conditions. Resistance to major hydroclimatic events can depend very much on the recent history of a biophysical system (Brunsden, 1992), including the effects of prolonged dry or wet weather (Wolfe *et al*., submitted). If adequate data were available, the time series analysis of climate could be linked to the spatial modeling of landscape sensitivity by relating the probabilities of hydroclimatic events to the properties of biophysical systems and soil landscapes that control resistance or amplify disturbance. A serious limitation of this approach, however, is the point distribution and low spatial resolution of climate records in contrast to the spatially continuous surveys of land cover, geology, topography and soil.

Geomorphic and ecological responses to a change in controls (landscape sensitivity) and the ratio of resistance to disturbance (the landscape change safety factor) exist at all scales, although landscape implies a regional scale. Spatial scale "is a vital element of landscape sensitivity" (Brunsden 1993: 11) and "permeates" hierarchy theory (de Boer, 1992), the formal study of the hierarchical structure of complex systems (Allen and Starr, 1982). Ecologists have embraced the concept of hierarchy, and elevated it to the status of theory (O'Neill *et al.*, 1986; Salthe, 1985). Some aspects of hierarchy theory, as applied to ecosystems, do not apply to geophysical systems because they are exclusively aggregative, that is, they are collectives of basic units (*e.g*., landforms) that physically exist independent of the system (Valentine and May, 1992). Conversely, cells do not exist independent of organisms, which in turn will perish outside a community. Slopes, on the other hand, exist whether or not they contribute sediment and runoff to the drainage basin in which they are located.

The nested hierarchical structure of landscapes and drainage networks is implicit in the study of landforms and hydrologic systems and underlies some of the classic works in geomorphology (Strahler, 1952; Schumm and Lichty, 1965). Earth scientists, however, generally have not adopted the notions and terminology of hierarchy theory. This may reflect a preference for empirical research, and especially field work (Baker and Twidale, 1991). This author is aware of only two papers (de Boer, 1992; Haigh, 1987) that specifically address the application of hierarchies to geomorphology. Furthermore, these papers consider only the heuristic value, while here I attempt to consider the practical applications of an hierarchical perspective to the spatially-explicit modeling of potential geomorphic responses to climate change and variability.

The concepts of a "triad" of adjacent levels and the "focal" (central) level of greatest interest (Valentine and May, 1996) are applied to geomorphology in Table 2. This arbitrary classification of time and space is an attempt to deal conceptually with the transfer of models of geomorphic systems among scales. Although hierarchical level is defined in terms of geographic features and spatial scale, there is an inherent increase in time spanned at progressively higher levels. In Table 2, time is scaled according to Schumm and Lichty (1965). Relative to the focal level, the next coarser scale provides context, that is, the initial or boundary conditions for processes which operate at the focal level, but are measured and modeled at the higher resolution of the next lower level.

Resistance and disturbance have different meaning across levels of the hierarchy, as variables emerge at levels below which they are irrelevant or simply do not exist. These emergent variables typically represent the interaction of processes and integration of responses, for

example (Table 3), inter-annual to decadal climatic variability, the synthesis of climatic observations over time, and the relative order or degree of coupling of landscape elements. Controls and responses must be synthesized for modeling and mapping at higher levels, as the cumulative outcome of processes operating locally is expressed over larger areas. Local variability cannot be resolved at a higher level at which patterns correlate with emergent variables, although the smaller units and local variation remained stored at their original scale in the GIS, as the (relational) data base is in itself is a nested hierarchy. When complex models are applied without explicit reference to scale, the "spatiotemporal integrity and characteristic scale" (Valentine and May, 1996: 23-33) of the variables tend to get masked or lost. Reference to scale includes an explicit spatial data structure and spatial models of specific variables, as opposed to mapping the output of a model that incorporates many variables. Similarly, synthetic landscapes, constructed from variables and relationships measured at finer scales, are a more rigorous approach to scale linkage than statistical smoothing, whereby dominant or significant features can be lost, replaced or masked by averaged results (Thorn, 1988: 85).

5. Discussion

The spatial modeling of the hydroclimatic disturbance of soil landscapes involves the coupling of a digital geographic data base and models that are appropriate in terms of scale and place. Literature on the role of scale in ecology and geomorphology (Allen and Starr, 1982; Church, 1996; de Boer, 1992; Harvey, 1968; Haig, 1987; Hostetler, 1994; Kennedy, 1977; Kirkby *et al*., 1996; Klemes, 1983; Leven, 1992; O'Neill *et al*., 1986; Phillips, 1988; Saab, 1999; Willgoose *et al*., 1992) and a conceptual framework based on landscape sensitivity and hierarchy theory suggest the following implications for the modeling of geomorphic response to climate at various scales.

1. Because disturbance and resistance have spatiotemporal dimensions and characteristic scale, their relative magnitudes, or the landscape change safety factor, is hierarchical. Controls and responses, and therefore landscape sensitivity, also occur at various scales. Sensitivity can exist over large areas and at coarse scales, for example, in dune fields where resistance to wind tends to uniformly low, or in densely dissected terrain, where potential disturbance is uniformly high. Scarps, valley heads and long or windward slopes, on the other hand, can represent islands of sensitivity which are located in otherwise insensitive landscapes and thus detectable only at fine scales. This local instability can be expressed at coarser scales as basin sediment yield and the growth of channel networks.

2. The spatial aggregation of details cannot reproduce structures and dynamics that emerge only at coarse scales. The regional evaluation of landscape sensitivity therefore requires both the synthesis of local spatiotemporal variability and the modeling of emergent controls and responses. Whereas processes at adjacent levels may differ significantly in rate, they are not independent (Phillips, 1988). Local, quasi-continuous activity can predispose landscapes to events of higher magnitude and lower frequency operating at a coarse scale. They can also produce resistant sediments (*e.g.,* lag deposits) and stable (graded) landforms. Processes which operate at a coarse spatiotemporal scale (e.g., tectonic events; major floods and

landslides) establish new boundary conditions which cause geomorphic systems to react with accelerated activity at finer temporal and spatial scales.

3. Geomorphic history and physical geography observable above the focal level sets the context and constraints on regional landscape sensitivity. Every landscape has elements that resist change (*i.e.*, are unresponsive to changes in controls) by virtue of geomorphic history and surficial geology. Unless a landscape is "saturated" by a dominant process (Haigh, 1987: 190), scaling up involves moving up the hierarchy from responsive (time-independent) slopes and channels to encompass (time-dependent) landscapes that correspond to past processes and resist change. Because stream channels act as conduits of geomorphic activity, largely inactive drainage networks inherited from a wetter paleoclimate, can be a locus of future geomorphic activity. In the southern Canadian plains, geomorphic activity is concentrated in the vicinity of large meltwater channels and incised tributary valleys. The intervening landscapes, mostly late-Pleistocene till and lake plains are largely inactive. However, the response of these glacial landforms and soils to cultivation in this century (Martz and de Jong, 1991; Mermut *et al*., 1983; Pennock *et al*., 1995) demonstrates their sensitivity to disturbance, which is potentially accelerated by climate variability and change.

4. Models based on present conditions and processes become a less relevant and accurate basis for forecasting the future and explaining the past. The fine scale also fails to capture regional interactions among systems and the spatiotemporal context of contemporary processes and systems. Coarse-scale models should include historical variables. At a coarse scale, the immediate hydroclimatic controls on geomorphic processes are not measurable. Rather, the relevant variables are regional climate, surface geology, land cover and relative relief. The impacts of climate change are expressed as changes in regional sediment yields and changing productivity of soil landscapes.

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Table 1. Geographic characteristics of the mixed grass prairie ecoregion of the southern Canadian plains.

General	
• 138,600 km^2	• > 50% of Canada's agricultural land
Ecoclimate	
• subhumid to semiarid	• mixed grass prairie
• high inter-annual climatic variability	• extreme temperature seasonality
Hydrography	
• major rivers are throughflowing	• significant snow melt runoff
• mostly intermittent streams	• large area of internal drainage
Geomorphology	
• poorly integrated drainage network	• underfit streams in glacial meltwater valleys
• glaciated sedimentary basin	• weakly linked slopes and channels

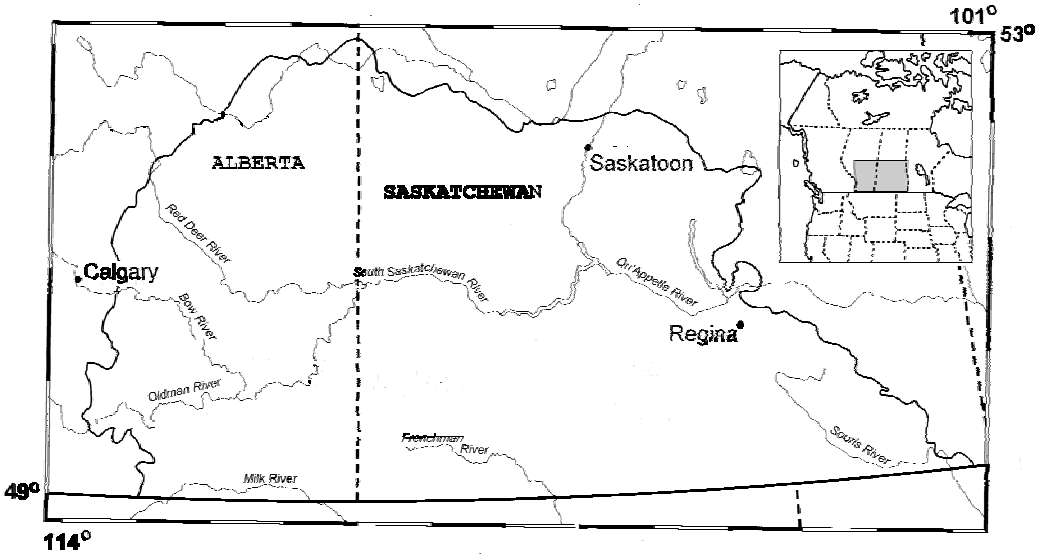
Table 2. Scales of geomorphic systems: The triadic hierarchy

Level	**Function**	**Spatiotemporal characteristics**
physiographic divisions	boundary conditions	cyclic; substitution of space for time
soil landscapes and small watersheds	focal level for environmental problems	graded; scaling up from slopes and channels
slopes and channels	process mechanics	steady (time independence); integration of events over small areas and short time spans

Table 3. A triadic hierarchy of landscape sensitivity: Some sources and controls of disturbance and resistance

Level	Disturbance	Resistance
physiographic divisions	• climatic change: frequency and magnitude of hydroclimatic events • tectonism • intrinsic geomorphic thresholds in large systems	• climatic change: surface and sub-surface water balances • ecoclimate and surficial geology • geomorphic history
soil landscapes and small watersheds	• climatic variability • major hydroclimatic events • coupling of systems	• landscape disorder • land cover • shear strength of surficial materials
slopes and channels	• hydroclimatic events • soil hydraulic conductivity • local relief and slope	• channel roughness • slope morphology • plant cover

Figure 1. A map of the southern Canadian plains. The solid bold line is the boundary of the subhumid mixed grass prairie ecoregion and brown soil zone.



Appendix D: The Geoenvironmental Mapping of Rainfall Erosion Risk in Southwestern Saskatchewan

In Geoenvironmental Mapping: Method, Theory and Practice; edited by P. Bobrowsky, Balkema, Rotterdam.

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INTRODUCTION

The Geological Survey of Canada initiated the Palliser Triangle Global Change Project in 1991 to evaluate linkages between Holocene climate and regional geomorphic processes in the driest part of the Interior Plains of western Canada (Lemmen et al. 1993). A major component of this project is the evaluation of soil landscape sensitivity to climatic change and variability (Sauchyn 1997). This paper describes and demonstrates a methodology for modeling and mapping potential rainfall erosion for a case study area in southwestern Saskatchewan, near the geographic centre of the Prairie Ecozone (Fig. 1).

The EuroCanadian history of the Prairie Ecozone has been characterized by a continuous adjustment of land use and settlement to climatic variability, defined as the periodic fluctuation of atmospheric conditions (e.g., drought, early frosts, major storms). Now public institutions have begun to address the potential impacts of climatic change, defined as a significant departure from "previous average conditions" (Environment Canada 1995: 49). The Canadian Climate Centre's general circulation model predicts that, in southern Canada, the largest CO_2-induced rise in mean surface temperature will occur in the Interior Plains (Boer et al. 1992). The latest projections suggest net average warming of 4–6° C by 2050 AD (Government of Canada, 1997). Most models also project increased average winter precipitation but with decreased net soil moisture and water resources in summer. Various studies (e.g., Williams et al. 1987, Schweger and Hooey 1991) have considered the potential direct or 'first-order' impacts of global climatic change on prairie agriculture. Less attention has been paid to indirect impacts of climatic variability and change on soil and water resources and on rates of earth surface processes (e.g., Wheaton 1984, Favis-Mortlock & Boardman 1995). Furthermore, unlike the spatially-explicit modeling and mapping of landscapes sensitivity described here, climate impact models or forecasts commonly are based on the general characteristics of an area (e.g., an ecological or political region) or on parameters evaluated at point locations (e.g., climate stations or grid intersections).

BACKGROUND

Brunsden and Thornes (1979: 476) defined landscape sensitivity as "the likelihood that a given change in the controls of a system will produce a sensible, recognizable and persistent response". In the dry, tectonically-stable southern Canadian Interior Plains, surface processes are climatically-driven. Soil landscapes respond to disturbances (hydroclimatic events) that exceed the resistance of soil landscapes to change. For the purposes of our study, landscape sensitivity can therefore be expressed in terms of a landscape change safety factor: "the ratio of the magnitude of barriers to change [resistance] to the magnitude of the disturbing forces" (Brunsden and Thornes 1979: 476) and determined by juxtaposing digital maps of disturbance and resistance, and categorizing the spatial covariation.

Because unstable landscapes tend to attract geomorphologists and engineers, information is available on the distribution and dynamics of active sand dunes, badlands and landslides (Campbell 1982, Wolfe et al. 1995, Sauchyn and Lemmen, 1996). The function of the methodology described here is to identify the metastable (sensitive) landscapes by differentiating them from those that are currently unstable and those that will likely not produce a sensible, recognizable and persistent response to climatic variability and change. We lack sufficient understanding of the Canadian plains to define the topographic, soil, and land cover thresholds that separate landscape stability and metastability. We can at least, however, place soil landscapes on a continuum between unstable and most stable according to the relative magnitudes of potential disturbances and resistance to change. The many studies of agricultural soil loss in this region (e.g., Mermut et al. 1983, Pennock & de Jong 1990, Martz & de Jong 1991, Pennock et al. 1995) enable some verification of the predicted sensitivities.

To implement this methodology with a geographic information system (GIS), expressions of disturbance and resistance must be derived from the variables in a digital geographic database (Table 1). The many existing models which predict soil loss or landscape change incorporate disturbance and resistance, but none of these models are suited to the unique combination of scale, purpose and landscape considered here. "Spatial scale is a vital element of landscape sensitivity because, with space, change becomes increasingly diversified and complex and prediction becomes less and less certain." (Brunsden 1993: 11). Geomorphic modeling typically is at the scale of slopes, channels or small watersheds (e.g., Kirkby 1993), while agricultural soil loss commonly is predicted by extrapolating empirical equations, notably the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1978), sometimes over large areas (e.g., Logan et al. 1982, Snell 1985). This requires judicious interpretation of the soil loss predictions, because parameter values averaged over heterogeneous map units represent a misuse of these empirical field-scale models (Wischmeier 1976, Roels 1985). Mapping individual fields or slopes over large areas is technically feasible with a GIS (Sauchyn 1993a), but this degree of spatial resolution would serve little purpose relative to the scale of agricultural land use in southwestern Saskatchewan. Furthermore, the data processing, storage and analysis required would consume major computing resources. When 1:100,000 soil surveys and 1:50,000 slope polygons were combined for one 1:250,000 map sheet, slightly less than 100,000 unique soil landscapes were identified (Ambrosi 1995), after small map units (< 1 ha) had been eliminated.

In addition to the difference in scale, most erosion models assume or are derived from landscapes with interrelated slopes and channels. In the southern Canadian Interior Plains, most landforms and surficial deposits are the product of late-Pleistocene deglaciation. As the result of

this short geomorphic history and the dry climate, the landscape is poorly integrated. There are few permanent streams and large areas are internally drained by intermittent stream flow into shallow saline lakes. The order and characteristic landforms of a well-developed fluvial landscape are lacking (Sauchyn 1993b). Thus, for example, rates of erosion on cropland are 2-3 times higher than sediment yields in small watersheds (Carson & Associates 1990). Eroded soil is mainly redistributed within local landscapes, especially in the hummocky moraine (Ashmore & Day1988, Martz & de Jong 1991). Empirical soil loss equations developed for landscapes beyond the limit of late-Pleistocene glaciation have been applied to the Canadian plains with limited success (Pennock & de Jong 1990). Although cropland is subject to tillage erosion, the redistribution of soil as a function of topography and drainage is analogous to accelerated erosion on uncultivated slopes.

Our objective is not maps of soil loss and gain, but rather regional scale maps that identify combinations of soil, landform and land cover that may respond to climatic variability and change with changes in the rates of earth surface processes. The identification and mapping of metastable (sensitive) soil landscapes at a regional scale (1: 100,000) differs significantly from predicting soil loss from fields and from simulating the evolution of slopes or channels. The remainder of this paper demonstrates the modeling and mapping of rainfall erosion potential, and then considers how the regional analysis of disturbance and resistance also can be applied to wind erosion and mass wasting.

MAPPING RAINFALL EROSION POTENTIAL

Kirkby & Cox (1995) introduced an index of Cumulative Soil Erosion Potential:

$$CSEP = 2N_0 r_0^2 \, exp(-h/r_0) \qquad (1)$$

where, conceptually, h is the threshold soil water storage, and N_0 and r_0 are "empirical parameters that are fitted to the [gamma] distribution in the neighbourhood of a one year recurrence interval" (Kirkby & Cox 1995: 335-336). Numerically, h can be derived for a unit depth of topsoil from soil hydraulic conductivity, N_0 is the mean number of rain days per year, and r_0 is mean rainfall per rain day. By itself, the CSEP "provides a powerful and physically based methodology for estimating the climatic element in soil erosion" (Kirkby & Cox 1995: 351), but it also can be embedded in a more complete erosion model, as demonstrated below with the use a topographic variable. The soil water storage term (h) incorporates the influence of grain size, and is less dependent on surface conditions than infiltration rate. The CSEP also can be disaggregated by month to include seasonal effects, and assumes a gamma distribution for a better fit to rainfall data than the general exponential curve.

To demonstrate a regional application of the CSEP, soil landscapes were defined from the digital soil and topographic data for six contiguous 1:50,000 NTS map sheets (72J 4,5 &12; 72K 1, 8 & 9) in southwestern Saskatchewan (Fig. 1). The rainfall variables were evaluated using daily climatic data from Swift Current, Gull Lake, Pennant, High Point and Beechy for the thirty-year "normal" period, 1965-1994. Values of N_0 and r_0 were assigned to each soil landscape from the nearest climatic station. Proximity to a climate station was determined by constructing

Thiessen polygons and overlaying these on the map of soil landscapes (Fig. 2). Threshold water storage capacity (h) was computed as the product of saturated hydraulic conductivity (Ksat) and six hours, a duration commonly used for the intensity-duration-frequency analysis of rainfall data (Gray, 1970). This assumes that overland flow, and thereby rill erosion and sheet wash, are produced once the soil is saturated, when infiltration is governed by the saturated hydraulic conductivity.

Because parent material (surficial geology) and synoptic climate have a regional distribution, soil series and precipitation can be modelled and mapped with relatively coarse spatial resolution. The topographic control of rainfall erosion, on the other hand, is at the scale of individual hillslopes. With the availability of topographic data at scales of 1:20,000 to 1:50,000 (Table 1), the product of the CSEP and a slope term ($\tan \theta$) represents a catchment-scale index of rainfall erosion potential. In the morainal landscapes of the northern Great Plains, most slopes are relatively short and thus slope gradient is more variable than slope length. The tangent of slope gradient is dimensionless. It also increases exponentially with increasing slope, and thus so does the potential for erosion, as the shearing forces on hillslopes increases as a sine function of slope gradient.

A triangulated irregular network was derived from the digital contours for each of the six topographic maps. This network of more than 100,000 polygons per map sheet was then filtered to achieve a regional topographic model. Initially polygons smaller in area than 10,000 km^2 were "eliminated" by removing the longest boundary shared with a polygon larger than the threshold size. Because this automated procedure removed nearly all of the steep slopes, the size limit was lowered to 2500 km^2 for polygons with slopes above 10°. These limits of polygon size and slope were completely arbitrary and serve only to reduce the complexity of the spatial model, rather than capture landforms of particular size or morphology. The number of unique polygons was further reduced by rounding the slope values to the nearest whole degree and "dissolving" boundaries between map units with the same slope. Slope gradient data were assigned to the soil polygons by superimposing the soil map boundaries on the filtered slope maps and computing summary statistics from the slope data enclosed by each soil polygon boundary. Relative rainfall erosion potential was then computed for each soil landscape as the product of the CSEP (equation 1) and the tangent of the mean slope. The assumption that slope gradient and climate variables have equal influence on erosion hazard is supported by physically-based (Kirkby, 1993) and empirical (Wischmeier & Smith, 1978) modeling of hillslope soil loss and sediment transport.

Relative classes of rainfall erosion potential (Table 2) were arbitrarily defined to reflect the distribution of potential rainfall erosion throughout the Prairie Ecozone, not just in the case study area mapped in Figure 2. The number and area of soil polygons in each erosion potential class (Table 3) reveals the right-skewed distribution typical of many natural phenomena. Almost 70% of the map area has no or negligible rainfall erosion potential (< 1). The class intervals increase in size to reflect the decreasing frequency of successively higher erosion potential. Although about 14% of the map area has very high erosion potential, nearly all these map units correspond to valley sides. The case study area was deliberately chosen to represent the complete range of erosion potential by encompassing major sections of the South Saskatchewan river valley, across the northern fifth of the mapped area, and the valley of Swift Current Creek, which trends diagonally across the bottom third of the map and then northward, northwest of Swift Current. The spatial correlation of high erosion potential and river valleys reflects the use slope as the only topographic variable.

High erosion potential also occurs on undulating topography in the middle of the map, where some heavy soils have low saturated hydraulic conductivity and therefore low threshold water storage capacity. The influence of the rainfall variables is evident where erosion potential changes by one class across a climate polygon boundary but within a soil landscape. Precipitation amounts and frequencies obviously do not change across hypothetical boundaries and thus the erosion potential probably should be interpreted as intermediate between the adjacent erosion classes. This problem with abstract boundaries is, of course, common to the vector representation of all spatially continuous phenomena.

FURTHER MODELING AND MAPPING

The appeal of a simple physically-based model, like the CSEP, is its applicability to a range of small map scales. At the coarse regional scale, "it is necessary to suppress topographic and soil detail, leaving only broad regional differences associated with lithology and climate" (Kirkby & Cox 1995: 334). As data for evaluating the CSEP increase in resolution, the model can be extended until it approaches the more complex modeling of soil and sediment yield at the scale of landforms and small watersheds. In the case study described above, a simple topographic factor was added. Other possible extensions of the CSEP include the computation of monthly rainfall totals to account for seasonality, the use of other theoretical frequency distributions to better fit rainfall data, and incorporating the influence of land cover on soil water storage. These additional or alternative terms permit further modeling of geomorphic responses to climatic variability and change.

Whereas rainfall runoff is the most widespread disturbance of soil landscapes in the southern Canadian Interior Plains, the modeling of landscape sensitivity in this region also requires expressions of potential mass wasting and wind erosion, and data on the distribution of resistance to all three geomorphic agents. These spatial models of disturbance and resistance must be derived from variables in the digital geographic database (Table 1). Dimensionless expressions of the topographic potential for mass wasting include slope gradient, the quotient of local and regional relief, or a composite index incorporating both gradient and relief. Because the southern Interior Plains are underlain by poorly-consolidated Quaternary sediments and Cretaceous bedrock, the potential for mass wasting occurs where the disturbance term is relatively high, that is, in the meltwater valleys, incised tributary valleys and uplands (Sauchyn, in press). Conversely, the distribution of potential wind erosion will reflect almost entirely the geography of resistance, as wind velocities exceed critical transport thresholds throughout the Prairie Ecozone (Muhs & Wolfe, in press). The ratio of precipitation to evapotranspiration (P/PE) is a good index of resistance, because it accounts for the distribution of both soil moisture and vegetation (Wolfe 1997). Cumulative wind energy or magnitude-frequency (Muhs and Maat 1993) is the basis for an index of the climatic potential for wind erosion (i.e., the disturbance factor). More specific climatic parameters include drift potential, the scalar sum of all winds capable of moving sand, and resultant drift potential, the vector sum of all sand-moving winds (Fryberger & Dean 1979).

Whereas the potential disturbance by water, wind and gravity can be expressed numerically, most of the resistance data, such as land use and soil texture, are categorical. Much empirical data would be required to convert soil and vegetation types to quantitative measures of resistance

(e.g., shear strength, boundary layer roughness). Furthermore, agricultural land cover changes annually and seasonally. Since human responses to climate are beyond the scope of this study, there are only three relevant land cover distributions: classified Landsat TM imagery from 1991-92 (Table 1), pre-settlement vegetation (i.e., mixed grass prairie) and departures from pre-settlement or 1991-92 land cover assuming specific changes in temperature and/or precipitation. Some resistance terms can be expressed numerically because they are directly related to topography or climate, which are readily quantifiable. These include a measure of landscape disorder, the P/PE ratio, and persistent water deficit (drought) or surplus which reduce resistance to surface erosion and landsliding, respectively. Some types of resistance cannot be evaluated from commonly mapped data because they reflect the geomorphic history of a soil landscapes (Brunsden 1993).

Use of GIS and a digital geographic database enables a spatially continuous assessment of landscape sensitivity over large areas, as opposed to the modelling of climatic parameters at point locations (i.e., climate stations or grid intersections) or predicting change to natural or human systems without specific reference to location. This distinction separates our mapping of landscape sensitivity from most other climatic impact studies. This mapping will conclude by superimposing digital maps of the climatic and topographic potential for rainfall erosion, wind erosion and mass wasting on maps of the relative resistance provided by various soil textures, actual land covers, simulated land covers, and landform morphologies. All maps are tentative, pending the verification of relative landscape sensitivity from existing estimates of soil loss and redistribution in various soil landscapes (e.g., Mermut, Acton & Eilers, 1983.; Pennock, Lemmen & de Jong, 1995).

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Table 1. The digital geographic database for southwestern Saskatchewan and southeastern Alberta

Digital maps	**Scale***	**Source**	**Region or Map Sheet(s)**
Soil	1:1000	CLBBR	Alberta and Saskatchewan
	1:100	SIP	southwestern Saskatchewan
Surficial geology	1:250	David (1964)	72K
	1:250	Klassen (1991, 1992)	72F, 72G
	1:250	Shetson (1987)	southern Alberta
	1:500	SRC	72J, 72L, 72H
Land cover	1:50	SRC	southwestern Saskatchewan
Topography	1:50	CSMA	southwestern Saskatchewan (96 NTS sheets)
	1:20	ABSM	72E/09
	1:20	CSMA	Cypress Hills, Saskatchewan
	1:20	U of C	RMs 138 and 139
Climate	1:250	AES	Alberta and Saskatchewan

* scale of hardcopy map from which the data were derived or scale corresponding to the reolution of the data, expressed as a representative fraction with denominator in 1000s

Abbreviations: Saskatchewan Institute of Pedology (SIP), Central Survey and Mapping Agency (CSMA), University of Calgary (U of C), Geological Survey of Canada (GSC), Centre for Land and Biological Resource Research (CLBBR), Alberta Bureau of Surveys and Mapping (ABSM), Atmospheric Environment Service (AES), Rural Municipality (RM)

Table 2. Classification of Relative Rainfall Erosion Potential

CSEP *tan θ	Rainfall Erosion Potential
0	not applicable[1]
0	none[2]
0.01-1.0	negligible
1.01-3.0	low
3.01-5.0	moderate
5.01-10.0	high
> 10.0	very high

[1] water, no data, City of Swift Current
[2] slope = 0 or high water storage capacity relative to mean daily rainfall

Table 3. Percentage of Soil Polygons in Each Class

Erosion Potential	% of Area	% of Polygons
not applicable	2.5	6.4
none	22.7	23.2
negligible	47.1	40.6
low	8.5	9.4
moderate	2.8	3.3
high	2.2	3.2
very high	14.2	13.9

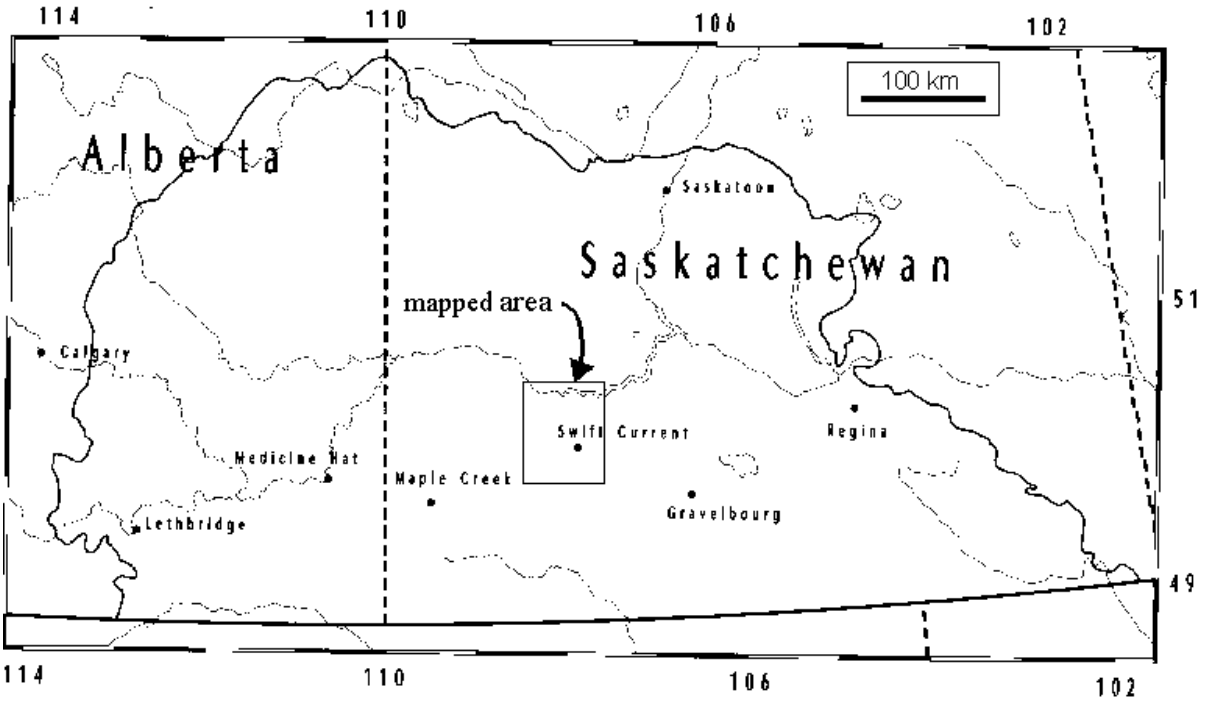


Figure 1. A map of the Prairie Provinces showing the Prairie and Boreal Plain Ecozones of the southern Canadian Interior Plains, which is bounded on west and northwest by Cordillera and on east and northeast by Shield. The rectangle around Swift Current is the area mapped in Figure 2

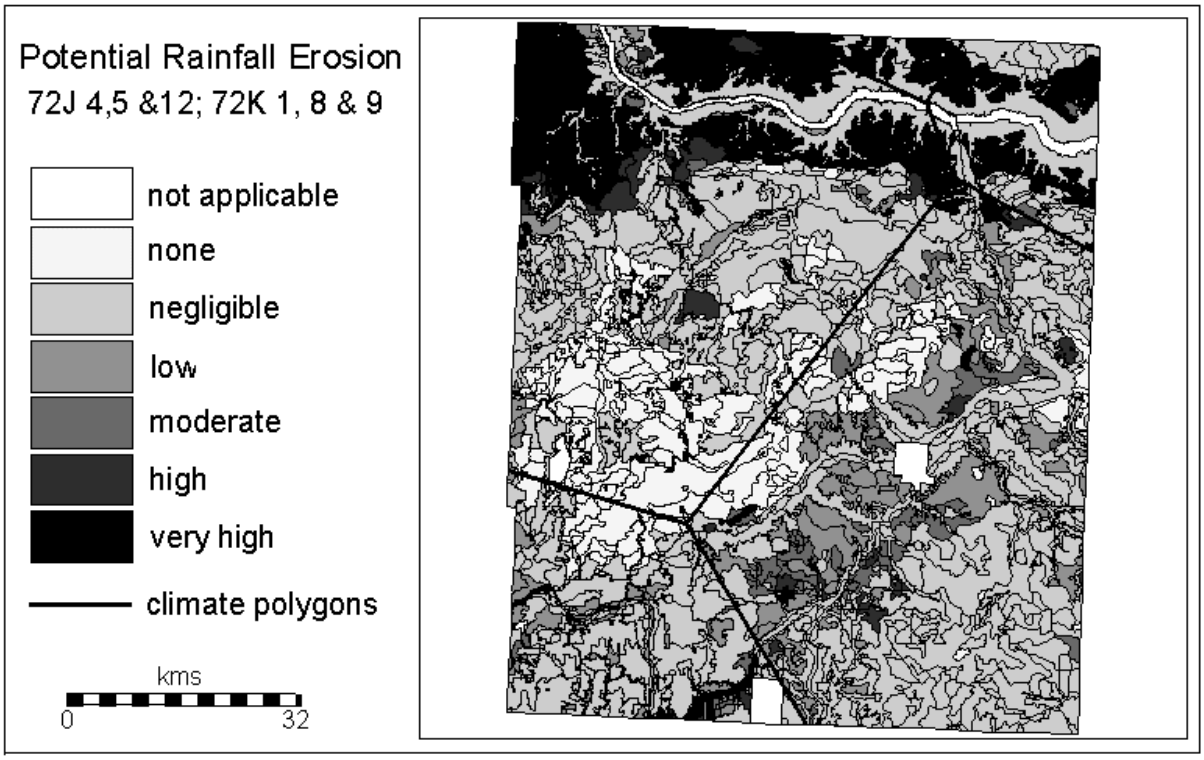


Figure 2. Rainfall erosion potential, NTS map sheets 72J 4,5 &12 and 72K 1, 8 & 9 in southwestern Saskatchewan. The heavy straight lines are the boundaries of Thiessen polygons corresponding to the five climate stations. The city of Swift Current is the white, almost rectangular, polygon southeast of the centre of the map.

Appendix E: A Methodology for Modeling Landscape Sensitivity based on synthetic landscapes (thesis proposal)

Master's Thesis Proposal

Samuel Kennedy, M.Sc. Candidate

Introduction

Landscape sensitivity is defined as "the likelihood that a change in the controls of a systems will produce a sensible, recognizable and persistent response" (Brunsden and Thornes, 1979: 476). Changes to a soil landscape occur when the disturbance of a geomorphic system exceeds resistance to it. Thus, the landscape sensitivity can be viewed in terms of a landscape change safety factor or the ratio between resisting forces and disturbing forces (Brunsden and Thornes, 1979).

In the dry and tectonically stable Canadian plains, climate is the driving force behind landscape processes. Thus, any change to the climate of the region has the potential to have a serious impact on soil landscapes. According to the Canadian Climate Centre's General Circulation Model, the increasing levels of CO_2 in the atmosphere are expected to greatest warming influence in the central plains of Canada (Boer *et al*., 1992). Increased stress on this already drought prone region has the potential to amplify the sensitivity of the soil landscapes. The application of a landscape sensitivity methodology will enable the identification of soil landscapes are potentially sensitive to climate change.

Geomorphic and engineering principles form the basis for many landscape models. These models tend to be derived from the study of process mechanics over small areas and at fine scales. The extrapolation of these models to coarser scales is problematic because the most relevant variables differ with changes in scale. This has tended to produce poor results in regional studies as process that have been observed to be very important at finer scale are not necessarily important at coarser scales. The Universal Soil Loss Equation (USLE) is a prime example of a model that is based on field scale observations and has been applied with poor results to regional scale studies (Wischmeier, 1976). Additionally, commonly used landscape models are based upon assumptions about hydrological processes that make them unsuited to the landscape of the Canadian plains. The recent geomorphic history of the region is related to the late-Pleistocene glaciation, which created a landscape that is poorly integrated, lacks fluvial dissection, drainage development and has large areas of internal drainage. This is problematic as most models assume landscapes that are hydraulically organized and developed. Thus, in order to apply a landscape sensitivity model to the prairies, the methodology must take into account the scale of study and the type of landscape involved (Sauchyn, 2001).

This thesis proposes to develop and apply a methodology that is based on the concept of synthetic landscapes and will enable the study of landscape sensitivity on a regional scale in the Interior Plains of western Canada. The methodology will be applied to a portion of southwestern Saskatchewan utilizing available digital data and a Geographic Information System (GIS).

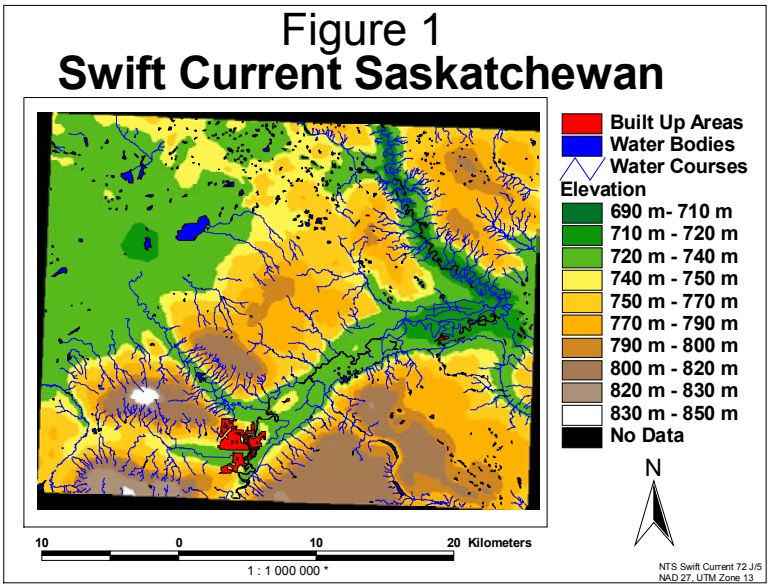
Objectives

The objectives of the thesis are:

- To develop a methodology for defining synthetic landscapes as a basis for the assessment of landscape sensitivity in Southwestern Saskatchewan on regional scale utilizing a GIS and the available digital data.
- To apply this methodology to a study area with a spatial extent that can be considered regional scale.
- To verify the model results by comparing certain aspects of the results with areas of known sensitivity in southern Saskatchewan.

Proposed Study Area and Rational

The proposed study area is a region centered on the city of Swift Current Saskatchewan. This region has a landscape that has responed to recent climatic changes. In the western part stable and active sand dunes respond to dry climate (David, 1993). These landscapes provides a means of testing the methodology as areas identified as sensitive should at the very least correspond to these known areas of sensitivity. The area also has soil landscapes that are representative of southwestern Saskatchewan, including a river valley system, areas of low relief and areas of poor and internal drainage (Figure 1).



not to scale

The study area, size and location are partly dependent on the type of soil landscapes, the available digital data and computational limitations. Representative soil landscapes are required to determine if the landscape sensitivity methodology can be applied in to the deranged hydrological environment of the southern prairies. The location of known areas of sensitivity is also required because if there is no potential for landscape sensitivity then there is no way to test the model.

Research Methodology

The methodologies used in the study of landscape sensitivity depend on the aspects of the landscape considered. At finer scales landscape variables are more easily quantifiable than at coarser scales. These studies tend to produce models based on the statistical or mathematical relationships among the variables and produce quantifiable results (Wicks and Bathurst, 1996; Mitasova et al., 1996). Other studies of landscapes, where variables cannot be easily or may not be mathematically quantifiable, tend to produce models that show the relative impact of variables on the landscape system (Mejia-Navarro et al., 1994; Kerenyi and Csorba, 1991, Kerenyi and Csorba, 1996). These types of landscape models can be applied at fine scales but they are more frequently used at coarser scales using GIS to summarize vast amounts of data (Lioubimtseva and Defourny, 1999). While certain landscape studies may be conceptually similar, the focus of the study and site-specific data require unique applications.

The proposed methodology is based on a series of papers by Sauchyn (1997; 2001; in press). These papers delve into the theoretical and practical basis for the mapping of landscape sensitivity in southwestern Saskatchewan. The papers propose a theoretical framework and various methods to overcome some of the potential problems associated with the landscapes in southern Saskatchewan, the scale of the region, and the available data. However, the application of the proposed methodology to the real world has been limited. Due to this limited application, certain aspects of the existing methodology may require modification before implementation.

The proposed methodology also is based partly on the theoretical work of Brunsden and Thornes (1979) and, in particular, the concept of landscape sensitivity as a product of resisting forces and disturbing forces. Certain data sets, such soil type or land cover, are not easily transformed into quantitative measurements of resistance or disturbance. Therefore, the mathematical relationship between disturbing forces and resisting forces cannot be calculated for all the data sets (Sauchyn, 1997). Another methodology is required in order to quantify the resisting and disturbing forces of all available data sets. One of the solutions proposed by Sauchyn (1997; in press) is the classification and delimitation of synthetic landscape based upon the relationships among topography, soil and land cover of each soil landscape unit.

Soils and Soil Maps

The use of the soil landscape unit as a spatial data structure for the study of landscape sensitivity is based upon the notion that the controls on the sensitivity of a landscape are represented in the types and distribution of soils. Different types of soil are produced by the combination of various climatic, hydrologic, topographic and geomorphic processes. The relative influence of these processes is reflected in types of soils and their distribution. The relationships between soil type and climate, drainage and landform is recognized and recorded in the mapping of soils. Additional information such as the slope, genetic parent material and the surface expression are included in soil maps (Soil Classification Working Group, 1998). Thus landscapes are inferred in the mapping of the type and distribution of soils.

Creation of a Soil Landscape Unit

Not all the relevant information required for the study of landscape sensitivity is provided within the soil map landscape units. In addition, some data provided with a digital soil survey, such as the slope, are less precise (ordinal) compared to the interval or ratio data available from digital topographic map sheets. This requires the incorporation of additional relevant landscape sensitivity information into the soil landscape unit. Through the addition of topographic, climatic, hydrographic and cultural information, the soils landscape units have the attributes necessary for the study of landscape sensitivity.

Synthetic Landscapes

Synthetic landscapes are landscapes defined by the statistical relationship among the attributes in each soil landscape unit, with the addition of relevant topographic, climatic, hydrographic and land cover information (Sauchyn, 1997). There is the potential for a large combination of attributes, however, patterns emerge whereby certain types of soil landscape have a similar combination of attributes. These soil landscape units can be considered as belonging to the same landscape type or system. Through the identification of the different landscape types or systems, the dominant attributes of these systems can be defined. The identification of the combination of dominant attributes is in essence the creation of synthetic landscapes. They have the dimensions and the physical meaning of the original data, but they the variability is reduced by classification. Synthetic landscapes are a means of linking spatial scales as the synthetic data at a coarse scale embody relationships among variables measured at the finer scales (Thorn, 1988). Therefore, synthetic landscapes are a promising approach to the study of landscape sensitivity on a regional scale.

There is no existing methodology to extract synthetic landscape types from the soil and topographic data. Through a combination of geo-processing and statistical analysis, the soil landscape can be grouped based upon similar combinations of attributes. be included in the soil landscape attributes. Matrix analysis will be used to group nominal data. The grouped dominant attributes of synthetic landscapes will be the basis for a regional and systematic analysis of landscape sensitivity.

Digital Data Acquisition

The required digital data is from a variety of existing sources and different scales (Table 1). Meta-data or data about data will also be required from all the sources to maintain the accuracy and reliability of the digital data.

Table 1

Digital Data	Scale of Original Data	Original Source
Soil Maps	1 : 100 000	Centre for Land and Biological Resource Research
	1 : 10 000	Saskatchewan Institute of Pedology
Topography and Hydrology	1 : 50 000	SaskGeomatics
Land Use Classification	1 : 50 000	SaskGeomatics
DEM (Digital Elevation Model)	1 : 20 000	University of Calgary
	1 : 20 000	SaskGeomatics
Meteorological Information		Environment Canada

Landscape Sensitivity Analysis

The analysis of landscape sensitivity using synthetic landscapes will be based upon information obtained from previous landscape and soil studies in the region. Using the dominant attributes of the synthetic landscapes and landscape and soil sensitivity information from previous studies, combinations of dominant or modal properties that make them more or less sensitive will be identified. In this way, the sensitive synthetic landscapes will be mapped.

Verification

The verification of results is not quantifiable, but by comparing the results with known areas of sensitivity in the study area, it is possible to determine if the model has successfully predicted these locations. Fieldwork may be required after the completion of the methodology in order to verify its results.

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Appendix F: Identifying Scale Domain Thresholds (thesis proposal)

Brent Joss
M.Sc. Candidate

Introduction

One of the most significant findings in the natural sciences is the identification of *natural scales* at which ecological processes and physical characteristics occur within the landscape. The existence of natural scales was revealed by a series of studies initially intended to identify appropriate sampling unit sizes for analyzing the spatial patterns of natural phenomena (Mead, 1974; Carpenter and Chaney, 1983; O'Neill *et al*., 1988; Carlile *et al*., 1989). Given that scale determines the range of patterns and processes that can be detected, the studies suggest that an appropriate scale be identified and explicitly stated for the phenomena under investigation. Studies evaluating the impact of spatial scales on the analysis of landscape further supported these findings (Turner *et al*., 1989; Moody and Woodcock, 1995).

The effects of scale are delineated by the concepts, *domain of scale* and *scale threshold* (Marceau, 1999). The former corresponds to regions of the scale continuum over which, for a certain phenomenon, patterns do not change with shifts in scale (Wiens, 1989; Marceau, 1999). Domains of scale are separated by thresholds, or relatively sharp transitions along the spatial scale spectrum, where a shift occurs in the relative importance of variables influencing a process (Meentemeyer, 1989; Wiens, 1989), thus producing differing spatial patterns. The importance of these concepts was emphasized through a series of studies undertaken to address three related issues: the identification of relevant domains of scale and scale thresholds, the evaluation of the scale effect on variables, and the creation of scaling laws to link information across scales (Marceau, 1999). The presence of characteristic scale ranges and transition zones may have important implications for environmental patterns and subsequent geographical interpretation (Wiens, 1989). For geographical analysis, identifying such spatial scale ranges and transition zones can have enormous practical value in adjusting sampling and modelling schemes and their resultant interpolation and interpretation.

Due to the economic and temporal logistics associated with gathering high-resolution regional data, a method for scaling data between differing spatial scales would be extremely beneficial. More importantly, a method for determining the degree to which a dataset can be scaled (domain threshold) is crucial. Identification of such limits or domains would allow findings at a particular scale to be extrapolated to other scales within a common domain. Information regarding such scale domains could possibly be attached to spatial data (or, embedded in digital data) in an attempt to prevent the extension of data between dissimilar domains and the errors that would result.

Purpose

The purpose of this research is to identify the scale domains of commonly available digital topographic and landcover datasets. The major focus will be on identifying the spatial thresholds to which the datasets can be reliably scaled-up. Resolution, a surrogate of scale (Goodchild and Proctor, 1998), will be progressively coarsened (aggregated) in an attempt to identify the effects of scaling-up upon each of the datasets. The spatial

patterns produced at each stage of aggregation will be quantitatively analyzed in a geographic information system (GIS) and used to identify the upper threshold for each dataset's domain of scale.
This research has been inspired by the previous works of Goodchild and Proctor (1998), Lam and Quattrochi (1992), and Wiens (1989). Their research addressed the scale problem associated with data integration and discussed methods currently utilized for effectively identifying scale domains and their associated thresholds.

Definitions

Operational definitions for the following fundamental concepts required for this thesis proposal will be discussed below:
'Scale'.
'Grain' and 'extent' components of scale.
'Resolution'.
'Up-scaling' and 'down-scaling'.
The operational linkages made between resolution and large/small scales.
'Aggregation' and the difference between 'individualistic' and 'ecological' fallacies.
'Fractals'.

Scale:
The term scale has generally been given two definitions. The first is the cartographic definition of scale where it is used to express a level of representation, where scale is the ratio or fraction between map distance and distance on the ground (Cao and Lam, 1997; Mayhew, 1997). In this use of scale, small-scale (small fraction) refers to a large area and large-scale (large fraction) refers to a small area. The second definition of scale is referred to as geographic scale where it is used to refer to the scale of an investigation or study, such as local, regional or national, and may additionally be concerned with the connections between events on a local, regional, or national scale (Cao and Lam, 1997; Mayhew, 1997). In this context, small-scale refers to a small area and large-scale refers to a large area. This study will use the cartographic definition of scale.

Grain and Extent:
Our ability to detect patterns is a function of both the extent and the grain of an investigation (O'Neill *et al*., 1986). Extent refers to the overall area encompassed by a study, while grain refers to the size of the individual units of observation. Extent and grain define the upper and lower limits of resolution for a study area (Wiens, 1989). Inferences about scale-dependency are constrained by the extent and grain of investigation. That is, generalizations cannot be made beyond the extent of investigation or for elements finer than the grain size. For logistical reasons, expanding the extent of an investigation usually involves increasing grain size. Therefore, the relationship between extent and grain carries a cost of diminished resolution when the ability to detect patterns over large areas is desired (Wiens, 1989).

Resolution
Spatial resolution refers to the smallest distinguishable parts of an object (Tobler, 1988), such as pixels in remotely sensed imagery or raster (grid-based) data models in Geographic Information Systems (GIS). Small-scale (cartographic scale) studies are commonly associated with coarse resolution, while fine resolution characterizes small-scale (cartographic scale) areas.

Scaling:
Mandelbrot (1983, p.18) defines scaling as, "invariance under certain transformations of scale." More generally, scaling refers to, "transferring data or information from one scale to another" (Marceau, 1999, p.349). Up-scaling refers to the means by which appropriate parameter values and processes are assigned to broader scales or coarser resolutions (Marceau, 1999). Conversely, down-scaling refers to the means by which parameter values and processes are allocated to finer scales or finer resolutions (Marceau, 1999).

Scale and Resolution

Small-scale/Coarse Resolution
Using the cartographic definition of scale, small-scale/coarse resolution infers relatively coarser spatial portrayal of features than does the term large-scale/fine resolution. A small-scale analysis would encompass a relatively larger area, usually with less spatial detail, than a large-scale analysis (Lillesand and Kiefer, 1994). For the purpose of this study the terms small-scale and coarse resolution will be used interchangeably.

Large-scale/Fine Resolution
Using the cartographic definition of scale, large-scale/fine resolution infers finer spatial portrayal of features than does the term small-scale/coarse resolution. A large-scale analysis would encompass a relatively smaller area, usually with greater spatial detail, than a small-scale analysis (Lillesand and Kiefer, 1994). For the purpose of this study the terms large-scale and fine resolution will be used interchangeably.

Aggregation and Individualistic/Ecological Fallacies
In geography spatial aggregation is widely practiced for scaling-up parameters and models from fine to coarse scales (Bian and Butler, 1999). Aggregation involves reducing the original spatial data to a smaller number of data units for the same spatial extent (Lillesand and Kiefer, 1994). As a result, each aggregated unit represents a larger area than the original unit and is referred to as having a coarser spatial resolution (Bian and Butler, 1999). Probably the most serious disadvantage of using aggregated data is the difficulty inherent in making valid multilevel inferences based on a single level of analysis. The attempt to impute macro-level relationships from micro-level relationships is what Alker (1969) terms the *individualistic fallacy*.
The *ecological fallacy* (Robinson, 1950) is the opposite of the individualistic fallacy and involves making inferences from higher to lower levels (down-scaling) of analysis. This problem commonly occurs when disaggregating data; that is, whenever the number of spatial units used to represent the spatial data is increased resulting in a finer spatial resolution.

Fractals
Mandelbrot defined a fractal as, "a shape made of parts similar to the whole in some way" (Mandelbrot, 1986, p. 18). The two main concepts underlying fractal theory are the statistical self-similar property and the fractal dimension (Cao and Lam, 1997; Xia and Clarke, 1997). The statistical self-similarity property of fractal geometry states that, "any portion of an object is similar in shape to the whole of the object at a reduced scale," (Cao and Lam, 1997). The fractal dimension concept is similar to the topological dimension that is associated with Euclidean geometry. However, the topological dimension is always an integer (1, 2, or 3 dimensional space) whereas the fractal dimension is a real number. The fractal dimension, *D*, measures the degree of irregularity or complexity of an object. Large values for the fractal dimension correspond to high levels of complexity.

Objectives
The objectives of the proposed research are:
- To construct a geo-database comprised of both topographic and landcover variables.
- To statistically identify variation within each dataset at each level of aggregation.
- To statistically measure the degree of spatial autocorrelation of each dataset at each level of aggregation.
- To statistically measure the fractal dimension of each dataset at each level of aggregation.
- To identify the upper-threshold for the domain of scale for each dataset.
- To identify the scales at which the studied variables may be successfully integrated.

Research Questions
Possible research questions to be addressed by the proposed research are:
- Can datasets collected at a specific scale be used successfully at coarser scales?
- At what level of aggregation (scale) does each dataset cease to significantly represent its original quality? In other words, what is the spatial threshold for each dataset's domain of scale?
- Do differing topographic variables (slope and aspect) share a common domain of scale?
- Do topographic and landcover variables (biomass) share a common domain of scale?
- How is variation influenced by aggregation?
- How is spatial autocorrelation influenced by aggregation?
- How is the fractal dimension influenced by aggregation?
- Do variation, spatial autocorrelation, and fractal dimension identify similar spatial thresholds?

Rationale
Growing awareness and concern over broad-scale issues such as global warming have emphasized the need to scale-up detailed knowledge acquired at fine scales. Given the complexity of scaling there is a need for multi-scale analyses and the development of scaling theories. Recognizing the existence of scale domains and their related spatial

thresholds can be considered a significant step towards the development of such scaling theories. Identification of scale domains and thresholds allows researchers to identify the limits to which information can be scaled. Knowledge of such limits, or thresholds, could possibly curtail the misapplication of spatial data.
Variance, spatial autocorrelation and fractal dimensions have been used extensively to identify scale domains and thresholds. Despite the large amount of research done in this area, the three measures have rarely been compared for their ability to identify similar spatial scale domains and thresholds for a common dataset. In addition, most research has been focused on identifying the scale domains and thresholds for a single spatial dataset and has not been interested in how domains differ between datasets for a common geographical area.
The proposed project will attempt to illustrate that the measures of variance, spatial autocorrelation and fractal dimension will identify similar scale domains and thresholds for a number of datasets covering a common geographic area.

Study Area

The proposed study area will be the Cypress Hills region located in southwestern Saskatchewan. The study area will cover approximately 6000 km^2, extensive enough to provide sufficient variations in topographic relief and landcover required by the proposed research. The location was selected for three main reasons. First, as previously mentioned, the area provides the topographic relief desired to produce a variety of terrain characteristics. Second, remotely sensed data is available for the area.

Third, digital topographic data for this region exists and, consequently, will permit observation of the impacts of up-scaling on both topographic and landcover datasets.

Philosophy

Positivism is the philosophical approach applied in this research. The collection and analysis of empirical data will facilitate the creation (deduction) of generalizations from facts in an effort to further knowledge in the area of interest.

Methodology

The proposed methodology is divided into five sections that will include a brief overview of the project, a description of the data to be acquired, the data processing and analysis procedures, the project deliverables, the possible limitations and possible solutions to these limitations.

Project Overview

The proposed research will attempt to identify the spatial thresholds related to the domain of scale for both topographic and landcover variables through the use of GIS technology and a suitable conceptual framework. The identification of the domain thresholds for each variable will increase awareness of the scaling limitations of each dataset and possibly curtail their misuse. The regional parameters that will be considered are those that are commonly used within both academia and commercial industry, specifically, the parameters of slope, aspect and the Normalized Difference Vegetation Index (NDVI). The effects of up-scaling via aggregation will be evaluated through the use of quantitative

techniques specifically related to the measurements of variance, spatial autocorrelation and fractal dimension. Given the relationships of variance, spatial autocorrelation and fractal dimension with successive aggregation, it is hypothesized that the spatial thresholds related to the domain of scale can be identified for each variable.

Data Acquisition

Data acquisition can be divided into two categories: 1) the acquisition of 1:50,000 topographic maps and their subsequent conversion to slope and aspect variables; and, 2) the acquisition of Landsat Thematic Mapper (TM) imagery and the subsequent extraction of spectral band information. The 1:50,000 topographic map sheets and the 30-meter resolution Landsat TM imagery will be acquired from SaskGeomatics.

Digital topographic maps and Landsat TM imagery were selected for three reasons. First, both share a common scale (resolution) of acquisition (30-meters). Second, a variety of information can be extracted from digital topographic maps and remotely sensed imagery. And, third, the datasets can be easily acquired.

Data Processing and Analysis

Geographic rectification is the main type of pre-processing required before analysis can commence. That is, all datasets will be geocoded, or positioned relative to a standard reference datum. The Universal Transverse Mercator (UTM) zone 13 projection and 1983 North American Datum (NAD83) will be used as the standard referencing system for this research because it is the referencing system in which the data will be acquired. Once the datasets are rectified, the original topographic data, in the form of vector contour lines, will be transformed to a triangulated irregular network (TIN) and subsequently to a raster grid theme. The resulting elevation grid theme will then be utilized to create themes of slope and aspect.

The Normalized Difference Vegetative Index (NDVI), a ratio calculated from the visible red and infrared bands, will be determined to produce a new grid coverage of biomass. The resulting raster grid data are considered ideal for studying data aggregation because their regular and uniform geometry follows a nested hierarchy that can be readily measured and presented (Bian and Butler, 1999).

The variables will then be progressively aggregated at intervals of 2 x 2, 4 x 4, 8 x 8, 16 x 16, …, 256 x 256. At each level of aggregation the variance, spatial autocorrelation and fractal dimension of each variable will be calculated and plotted to determine the spatial threshold for the domain of scale. Domains of scale and their related thresholds will be identified through three methods. The first approach will be based on the observation that variance increases as transitions are approached in hierarchical systems (O'Neill *et al.*, 1986). Peaks of unusually high variance indicate scales at which the between-group differences are especially large, suggesting that this may represent the scale of natural aggregation, or the boundary of a scale domain (Greig-Smith, 1952, 1979). Coincidence in the variance peaks of different variables may indicate common spatial scaling and the possibility of direct linkages (Greig-Smith, 1979; Schneider and Piatt, 1986).

The second approach will be based on the average squared difference (semi-variance) or the spatial autocorrelation between two points (two grid cells) which may be expressed as

a function of the distance between them to estimate the scale of patchiness in the system (Sokal and Oden, 1978; Burrough, 1983).
The third approach involves the application of fractal geometry to spatial patterns (Mandelbrot, 1983). Many physical systems display patterns that differ in detail at different scales but remain statistically 'self-similar' when the changes in pattern measurements are adjusted to the changes in measurement scale (Burrough, 1983). The way in which detail differs with scale can be described by the fractal dimension, *D*, which indexes the scale dependency of the pattern. Statistical self-similarity of patterns occurs when processes at fine scales propagate the patterns to broader scales, although self-similar patterns may also arise from the operation of different but complementary processes (Milne, 1988). A change in fractal dimension of a pattern, on the other hand, is an indication that different processes or constraints are dominant. Therefore, regions of fractal self-similarity of pattern may represent domains of scale whereas rapid changes in fractal dimension with small changes in measurement scale may indicate transition between scales (Wiens, 1989).

Project Deliverables
The project deliverables will consist of a set of digital files, hardcopy maps, graphs and a thesis. Digital files (GIS themes), hardcopy spatial maps and graphs produced will include a suite of maps for each variable at each level of aggregation and a series of graphs depicting the trends of the variance, spatial autocorrelation and fractal dimension with increasing aggregation.

The thesis will include the following components:
- A review of literature on the research topic.
- A summary of all data collection and analysis procedures used in identifying the domain of scale for each variable.
- A discussion of the results.
- An evaluation of the procedures conducted.
- A discussion on what factors to consider when attempting to identify the domain of scale.
- A summary of recommendations on how to improve the methodology used and the formulation of questions for future research.

Possible Limitations and Solutions
There are a number of conceivable limitations associated with the proposed methodology. These limitations include:
- Insufficient scale range or number of aggregations.
- The Modifiable Areal Unit Problem (MAUP).
- Neglect of time in the study.
- Computing the fractal dimension of a surface may be very computer intensive.
- The 'Edge Effect' associated with raster data.
- Direction dependency of semi-variograms.
- The self-similarity property underlying the original fractal model.

Range of scale or number of aggregations problem
The range of outlined aggregations may not be sufficient to illustrate a definite domain of scale or upper threshold for each of the variables examined. This problem could be solved by increasing the number of aggregations up to the highest allowable level within the specified study area.

Modifiable Areal Unit Problem (MAUP)
The Modifiable Areal Unit Problem (MAUP) originates from the fact that many different ways exist to divide a geographical study area into non-overlapping areal units for the purpose of spatial analysis. Usually, the principal criteria used in the definition of these units are the operational requirements of the study. As a result, none of these spatial units have any intrinsic geographical meaning. Therefore, if the areal units are arbitrary and modifiable, the value of any work based upon them may not possess any validity independent of the units which are being studied (Marceau, 1999).

Neglect of time in the study
Although time is acknowledged as an important component in understanding many environmental variables, it is, for the most part, ignored in this project. The focus of this study will be on spatial scale and the identification of domain thresholds within it. The time component and its associated domains of scale will not be discussed despite the inseparable nature of space and time. Therefore, the conclusions made should be considered 'pseudo' in nature because they are made on a fine time scale relative to the actual dynamics of the systems related to each examined variable (Wiens, 1989).

Computation of fractal dimension problem
The computation of the fractal dimension for each variable at every successive aggregation may be too labour intensive to be efficiently accomplished. A possible solution would be to employ discretion and calculate the fractal dimension for n^{th} aggregation level and/or for regions illustrating statistical thresholds by the other statistical measures (variance and spatial autocorrelation).

Edge effects in raster models
The edge effect is a common problem when running neighbourhood algorithms or performing aggregation on raster datasets. Neighbourhood or focal algorithms require that the value of a cell be determined by previous values of its neighbouring cells and, unless the modeler is very careful, cells at the border with fewer neighbours will behave differently resulting in 'edge effects' (ESRI, 2000). To nullify the 'edge effect' the grid cells abnormally treated (cells without a complete neighbourhood) will be assigned a value of zero and/or eliminated from statistical results.

Directional dependency of semi-variograms
Semi-variograms (graphs of variance) are direction dependent and will produce differing results with different directions (anisotropic). To prevent such a problem semi-variograms will be created for a variety of directions and comparisons will only be made between semi-variograms of common direction.

The fractal problem
The self-similarity property underlying Mandelbrot's (1983) fractal model assumes that the form or pattern of the spatial phenomenon remains unchanged throughout all scales, implying that fractal analysis cannot determine the scale of the spatial phenomenon from its form or pattern. The absolute definition of self-similarity is considered unacceptable by many, and has subsequently generated criticism on the application of fractals on spatial phenomena (Lam and Quattrochi, 1992).
Empirical studies have shown that most real-world curves and surfaces are not pure fractals with a constant *D* at all scales. Instead, *D* varies across a range of scales (Goodchild, 1980; Mark and Aronson, 1984). Therefore, *D* can be used to identify the scale changes of the spatial phenomenon (Lam and Quattrochi, 1992).

Schedule
Table 1: Schedule for proposed research

School Term	**Work/Activities**
Summer Semester 2001	Further literature review & Data collection.
Fall Semester 2001	Analyze results & Begin first draft.
Winter Semester 2002	Complete first draft and editing process & Thesis defense.

Summary
The purpose of this project is to identify the scale domains of commonly available digital topographic and landcover datasets. The major focus will be on the identification of the spatial thresholds to which the datasets can be reliably scaled-up. The study proposes a unique approach and will apply multiple methods used for recognizing scale domains and thresholds in an attempt to identify the domains and thresholds for both topographic and landcover variables. The study will show that the identification of scale domains and thresholds can provide users with vital information regarding the scaling limitations of commonly utilized datasets.

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Appendix G: Scale in Spatial Research

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I. Introduction

Scale is possibly the most important aspect of all research. It is a term used in the context of space, time and in many other dimensions of scientific research. Whether implicitly or explicitly stated as a component, scale is always a factor in research. It affects both spatial and temporal data in a number of ways and creates a variety of problems for many disciplines, especially geography.

Historically geography has been associated with scale and, although it acknowledges the importance of time, it is predominantly concerned with the scale of spatial features. The problems related to spatial scale are numerous, especially when attempting to scale, or transfer, data from one spatial scale to another. The need to scale-up fine-scale data has increased with the growing concern and awareness of global issues such as climate change. As a result, there has been a tremendous increase recently in efforts developing scaling theory and scaling techniques.

The recent emergence and global use of digital technology such as geographic information systems (GIS) and remote sensing systems have enabled the development of techniques for dealing with scale-related problems. The statistical ability of geographic information systems has equipped researchers with a valuable tool that has the ability to scale spatial data. But, despite the abilities of GIS and remote sensing techniques, the scaling of spatial data remains a problem.

The purpose of this paper is to identify the importance of scale in geographical research. It will briefly discuss the problems and major concepts underlying the scaling of spatial data. The concepts of characteristic (operational) scale, domain of scale and scale domain thresholds will be discussed and methods for identifying each will be reviewed. The current direction of scaling research will be discussed and recommendations will be made regarding the focus of future research.

II. Scale-Related Problems

The importance of scale has long been recognized in the discipline of geography. Scale affects the spatial patterns that are observed and the subsequent interpretations and decisions based upon such observations. Yet, despite its importance, the effects of scale on spatial analysis have rarely been researched.

The growing concern over global-scale problems has emphasized the need to scale-up fine-scale data to broader scales (Addicott *et al.*, 1987; O'Neill, 1988; Levin, 1992; De Cola and Montagne, 1993; van Gardingen, 1997). As a result, recent spatial research has focused on approaches for scaling spatial data and identifying their limitations. At present, researchers are attempting to answer a number of complex questions (Goodchild and Quattrochi, 1997). Some of these questions include:

- How can spatial data be scaled without compromising detail?
- What measures of scale will allow geographic detail to survive routine manipulations, such as the conversion from analogue to digital formats (Goodchild and Quattrochi, 1997)?
- What kinds of transformations of scale are available to scale-up or scale-down data?
- How are observations of spatial phenomena and processes affected by shifts in scale (Phillips, 1988)?
- How can the dominant processes affecting spatial structure be identified at each scale and how can their level of influence be measured?
- What are the impacts of scaling spatial data?
- Can spatial data be scaled, and can spatial data be scaled infinitely or are there limitations? If such limitations exist, how can we identify them?
- What variables and relationships are sensitive to scale changes (Fotheringham, 1983)?
- What is the potential for integrating scaling tools into existing spatial analysis software?
- How can information regarding scaling techniques and scaling limitations be distributed in an effective way?

Although complete solutions have not yet been produced, partial answers to many of these questions already exist (Goodchild and Quattrochi, 1997). The problem is that these partial solutions are scattered throughout many disciplines, making their integration and broad application difficult (Levin, 1992; Goodchild and Quattrochi, 1997). Integration of such findings is further complicated by the various spatial variables focused upon and the vernacular utilized by each discipline. That is, the effects of scale will be different for different spatial variables. For example, one would expect that the spatial pattern of (relatively) continuous spatial phenomena such as topography would be affected much differently by scaling techniques than the spatial pattern of more discrete phenomena such as landcover and landuse.

In addition to focusing on different spatial phenomena, disciplines also use their own dialect. Therefore, any given term often portrays a number of different meanings. For example, the term scale has a variety of meanings and correlates (Atkinson, 1997; Cao and Lam, 1997; Curran *et al.*, 1997; Goodchild and Quattrochi, 1997; Goodchild and Proctor, 1998; Marceau, 1999). The main definitions and correlates will be discussed below.

III. Definitions of Scale

Despite its importance, scale is probably one of the most ambiguous terms in research. In geography, scale is commonly used to refer to both the level of detail and to the spatial extent of a study. The former refers to the cartographic definition of scale where it is used to express a level of representation. In other words, scale in the cartographic sense refers to the ratio or fraction between map distance and distance on the ground (Atkinson, 1997; Bian, 1997; Cao and Lam, 1997; Curran *et al.*, 1997; Goodchild and Quattrochi, 1997; Mayhew, 1997; Squire and Gibson, 1997; Goodchild and Proctor, 1998; Marceau, 1999). In this use of scale, small-scale (small fraction) refers to a large area and large-scale (large fraction) refers to a small area. The latter definition is referred to as geographic scale. In the geographic sense scale refers to the scope of an investigation or study (local, regional or national) (Atkinson, 1997; Bian, 1997; Cao and Lam, 1997; Curran *et al.*, 1997; Goodchild and Quattrochi, 1997; Mayhew, 1997; Squire and

Gibson, 1997; Goodchild and Proctor, 1998; Marceau, 1999). In this context, small-scale refers to a small area and large-scale refers to a large area.

IV. Correlates of Scale

With the introduction of digital spatial datasets and geographic information systems a number of correlates for scale (representative fraction) have been created (Cao and Lam, 1997; Goodchild and Proctor, 1998). The three major scale correlates are resolution, the minimal mapping unit (MMU), and positional accuracy.

Spatial resolution refers to the smallest distinguishable parts of an object (Tobler, 1988), such as pixels in remotely sensed imagery or raster (grid-based) data models in Geographic Information Systems (GIS) (Forshaw, 1983; Irons, 1985). The correlation between resolution and scale can be illustrated with a remotely sensed dataset. Landsat imagery with 30-meter resolution corresponds to a scale of approximately 1:50,000 (Cao and Lam, 1997; Goodchild and Proctor, 1998).

The minimal mapping unit refers to the size of the smallest spatial unit shown in a spatial dataset (Goodchild and Quattrochi, 1997; Goodchild and Proctor, 1998). The minimal mapping unit is commonly calculated for thematic (vector) maps portraying spatial phenomena such as soils or vegetation cover. Scale can be calculated by establishing the relationship between the representative fraction and the MMU. For example, a MMU of one hectare (100m x 100m) would correspond to a representative fraction of approximately 1:100,000 (Goodchild and Proctor, 1998).

The third correlate, positional accuracy refers to measure of the differences between the positions of features portrayed in spatial dataset, and their true ground positions (Goodchild and Proctor, 1998; Bernhardsen, 1999). For example, a spatial dataset (map) with differences approximating 0.5 millimeters and a measured positional accuracy of 12 meters would correspond to a representative fraction of approximately 1:24,000 (12 / 0.0005) (Goodchild and Proctor, 1998).

V. Scaling

In general, scaling refers to, "transferring data or information from one scale to another" (Marceau, 1999, p.349). Hierarchy theory is the foundation of most scaling approaches (Grace *et al.*, 1997; Marceau, 1999). Therefore, within the hierarchical structure, spatial scaling can occur in both an upward and downward direction. Up-scaling refers to the means by which appropriate parameter values and processes are assigned to broader scales or coarser resolutions (Levin, 1993; Atkinson, 1997; Grace *et al.*, 1997; Marceau, 1999). In other words, it is the process of transforming the sampling frame from a small to a large geographic scale. Conversely, down-scaling refers to the means by which values are transferred to finer scales or finer resolutions (Atkinson, 1997; Grace *et al.*, 1997; Marceau, 1999).

VI. Aggregation

In geography spatial aggregation is widely practiced for scaling-up parameters and models from fine to coarse scales (Clark and Avery, 1976; Bian and Butler, 1999). Aggregation involves reducing the original spatial data to a smaller number of data units for the same spatial extent (Openshaw, 1977; Openshaw, 1984; Lillesand and Kiefer, 1994). As a result, each

aggregated unit represents a larger area than the original unit and is referred to as having a coarser spatial resolution (Bian and Butler, 1999). Probably the most serious disadvantage of using aggregated data is the difficulty inherent in making valid multilevel inferences based on a single level of analysis. The attempt to impute macro-level relationships from micro-level relationships is what Alker (1969) terms the *individualistic fallacy*.

The *ecological fallacy* (Robinson, 1950) is the opposite of the individualistic fallacy and involves making inferences from higher to lower levels (down-scaling) of analysis. This problem commonly occurs when disaggregating data; that is, whenever the number of spatial units used to represent the spatial data is increased resulting in a finer spatial resolution.

VII. Operational Scales, Scale Domains, and Scale Domain Thresholds

One of the most significant findings in the natural sciences is the identification of *natural scales* at which ecological processes and physical characteristics occur within the landscape. The existence of natural scales was revealed by a series of studies initially undertaken to identify appropriate sampling unit sizes for analyzing the spatial patterns of natural phenomena (Mead, 1974; Carpenter and Chaney, 1983; O'Neill *et al*., 1988; Carlile *et al*., 1989). Given that scale determines the range of patterns and processes that can be detected, the studies suggest that an appropriate (operational) scale be identified and explicitly stated for the phenomena under investigation. The operational scale (also called the characteristic scale) of a phenomenon is suggested to be the point along the scale continuum at which it is most variable (Moody and Woodcock, 1995; Turner *et al*., 1989a; Turner *et al.*, 1989b). Studies evaluating the impact of spatial scales on the analyses of topographic and landcover variables further support these findings (Moody and Woodcock, 1995; Turner *et al*., 1989a; Turner *et al.*, 1989b).

Closely related to the idea of operational scales are the two concepts *domain of scale* and *scale domain threshold* (Delcourt and Delcourt, 1988; Barnsley *et al.*, 1997; Curran *et al.*, 1997; Marceau, 1999). The former concept defines regions on the scale continuum over which, for a certain phenomenon, patterns do not change with shifts in scale (Wiens, 1989; Curran *et al.*, 1997; Marceau, 1999). Scale domains are separated by thresholds, or relatively sharp transitions along the spatial scale spectrum, where a shift occurs in the relative importance of variables influencing a process (Meentemeyer, 1989; Curran *et al.*, 1997; Wiens, 1989), thus producing differing spatial patterns. The importance of these concepts was emphasized through a series of studies undertaken to address three related issues: the identification of relevant domains of scale and scale thresholds, the evaluation of the scale effect on variables, and the creation of scaling laws to link information across scales (Watson, 1978; Marceau, 1999). The presence of characteristic scale ranges and transition zones may have important implications for environmental patterns and subsequent geographical interpretation (Harvey, 1968; Wiens, 1989). For geographical analysis, identifying such spatial scale ranges and transition zones can have enormous practical value in adjusting sampling and modelling schemes and their resultant interpolation and interpretation (Heuvelink, 1998).

The sheer economic and temporal logistics associated with gathering high-resolution regional data mean that a method for scaling data between differing spatial scales would be extremely beneficial. More importantly, a method for determining the degree to which a dataset can be scaled (the domain threshold) is crucial. Identification of such limits, or thresholds,

would allow findings at a particular scale to be extrapolated to other scales within a common domain. Information regarding such scale domains could possibly be attached to spatial data (or, embedded in digital data) in an attempt to prevent the extension of data between dissimilar domains and the errors that would result.

VIII. Approaches for Identifying Scale Domains and Thresholds

Domains of scale and their associated thresholds have usually been identified through analysis of variance, spatial autocorrelation and fractal dimension (Wiens, 1989).

i. Variance

Since all natural objects are structured and have characteristics that change in space and time, variability is both common and fundamental to all natural spatial phenomena (Marshall *et al.*, 1997). The significance of variability in scaling spatial data and in the identification of scale domains and thresholds is the manner in which it changes with shifts in scale (Nellis and Briggs, 1989; Marshall *et al.*, 1997; Woodcock, 1997; Seyfried, 1998). That is, variance has been observed to increase as scale transitions are approached in hierarchical systems (Coulson, 1978; O'Neill *et al.*, 1989). Peaks of unusually high variance indicate scales at which the between-group differences are especially large, suggesting that this may represent the scale of natural aggregation, or the boundary of a scale domain (Greig-Smith, 1952, 1979). Coincidence in the variance peaks of different spatial variables may indicate common spatial scaling and the possibility of direct linkages (Greig-Smith, 1979; Schneider and Piatt, 1986).

ii. Spatial Autocorrelation

The second approach is based on the average squared difference (semi-variance) or the spatial autocorrelation between two points (two grid cells) in the spatial data. The semi-variance or spatial autocorrelation is expressed as a function of the distance between them to estimate the scale of patchiness in the system (Sokal and Oden, 1978; Burrough, 1983; Qi and Wu, 1996).

Spatial autocorrelation refers to the ordering of a phenomenon with respect to geographic position (Qi and Wu, 1996). Most natural phenomena usually exhibit positive spatial autocorrelation which is the tendency for locations that are near in space to exhibit more similar characteristics than sites which are separated by greater distances (Tobler, 1969). Spatial autocorrelation, which is produced by the physical forcing of environmental variables or processes, is a general statistical property of natural variables observed across geographic space (Qi and Wu, 1996).

The semi-variogram, a graphical representation of semi-variance, is used to identify the scale of the measured spatial distribution through its shape (Curran, 1998). In theory, the semi-variogram double logarithmic plot should form a straight line but, in practice, many plots are curvilinear in shape with obvious plateaus or sills at certain scales (Lam and Quattrochi, 1992). These plateaus or sills indicate scale domain thresholds in the spatial data (Bian, 1997).

iii. Fractal Analysis

Benoit Mandelbrot defines a fractal as, "a shape made of parts similar to the whole in some way" (Mandelbrot, 1986, p. 18). The two main concepts underlying fractal theory are the statistical self-similar property and the fractal dimension (Burrough, 1981; Mandelbrot, 1983; Burrough, 1993; De Cola and Lam, 1993a; Lam and De Cola, 1993; Bian, 1997; Cao and Lam, 1997; Xia and Clarke, 1997). The statistical self-similarity property of fractal geometry states that, "any portion of an object is similar in shape to the whole of the object at a reduced scale," (Cao and Lam, 1997, p. 67). The fractal dimension concept is similar to the topological dimension that is associated with Euclidean geometry (De Cola and Lam, 1993b). However, the topological dimension is always an integer (1, 2, or 3 dimensional space) whereas the fractal dimension is a real number. The fractal dimension, *D*, measures the degree of irregularity or complexity of an object. Large values for the fractal dimension correspond to high levels of spatial complexity.

The self-similarity property underlying Mandelbrot's (1983) fractal model assumes that the form or pattern of a spatial phenomenon remains unchanged throughout all scales, implying that fractal analysis cannot determine the scale of the spatial phenomenon from its form or pattern (Wiens, 1989; Lam and Quattrochi, 1992). However, studies have shown that most real-world phenomena are not pure fractals with a constant *D* at all scales (Goodchild, 1980; Mark and Aronson, 1984). Therefore, it has been suggested that *D* can be used to identify the scale domains and thresholds of spatial phenomena (Wiens, 1989; Lam and Quattrochi, 1992).

The fractal approach for identifying scale domains and thresholds utilizes the fractal dimension, *D*, which indexes the scale dependency of the spatial pattern (Gilbert, 1989; Atkinson, 1997). That is, statistical self-similarity of spatial patterns occurs when processes at fine scales produce the same patterns at broader scales (Milne, 1988). A change in fractal dimension is an indication that different processes or constraints dominate at the new scale (Krummel, 1987). Therefore, it is suggested that scale ranges of fractal self-similarity represent domains of scale whereas rapid changes in fractal dimension indicate domain thresholds (Wiens, 1989; Souriau, 1994; Barnsley *et al.*, 1997; Curran *et al.*, 1997; Marceau, 1999).

IX. Prospects for Scaling

Given the complexity of the scale problem and the increasing demand for scaling data a number of future prospects have been identified. Literature on scaling have suggested that future work be directed towards developing guidelines for scaling spatial data, developing new technologies for scaling and solving the problems of current technology (Caldwell *et al.*, 1993; van Gardingen *et al.*, 1997).

It has been suggested that the future efforts of research be directed towards developing guidelines for scaling spatial data. It is recommended that guidelines include routines for assessing scale, the constraints and consistencies of spatial data at different scales, and the results of scaling spatial data (Caldwell *et al.*, 1993).

In addition to scaling guidelines, the development of new and the refinement of existing scaling technologies has also been identified as an area where future work is required. New technology and approaches for making integrative measurements are

contributing to the progress of scaling spatial data, and will continue to contribute with further advances (van Gardingen *et al.*, 1997).

X. Recommendations for Future Research

The importance of scale and the issues associated with scaling spatial data have long been recognized. Issues related to the scaling of spatial data (the concepts of scale domains and scale domain thresholds) have received attention from the research community but additional research is needed. Topics related to this area of research that require future investigation include: identifying the operational, or characteristic scale for different spatial phenomena, comparing the techniques utilized for identifying the scaling limitations (scale domains and thresholds) of spatial datasets, identifying the 'best' technique for identifying such limitations, comparing the limitations of various spatial datasets, and the dissemination and implementation of scaling information with spatial datasets.

i. Identifying Operational Scales for Spatial Phenomena

The identification of operational scales is critical for the proper observation and interpretation of spatial variables and processes. Although current research commonly identifies the operational scale of a spatial phenomenon as the point along the scale continuum at which it is most variable, further research is required (Moody and Woodcock, 1995; Turner *et al*., 1989a; Turner *et al.*, 1989b). That is, the point along the scale continuum at which a phenomenon displays its highest level of variability commonly coincides with the occurrence of a scale domain threshold. Therefore, the concepts of operational scales and scale domains contradict each other. The concept of scale domains suggests that only datasets sharing a common scale domain (range of scales) can be integrated. The probability of two spatial phenomena sharing the exact operational scale is minimal, and as a result, the chance of properly integrating the datasets is minute. Therefore, further work is required in redefining the concepts so they are complementary to one another.

ii. Comparing Techniques

Future scaling research should focus on comparing the existing techniques utilized for identifying spatial scale domains and their thresholds. Despite the amount of research performed in this area, little emphasis has been placed on comparing the ability of different approaches to identify similar spatial scale domains and thresholds for a common dataset.

Comparing and evaluating the techniques used to identify spatial scale domains and thresholds would be very beneficial. Comparison could provide researchers with information on: the differences between the techniques, the advantages and disadvantages of each, whether or not the techniques should be used in combination to identify scaling limitations, and possibly determine the most appropriate technique for identifying the scaling limitations of spatial datasets.

iii. Identifying the 'Best' Technique

It is apparent that not only has there been limited research performed on comparing approaches utilized to identify spatial scale domains and thresholds, but there has also been very little discussion about which technique is the most appropriate and/or reliable. Identification of the 'best' technique would allow standardized measurements of the scaling limitations to be made. Standardization would allow the scaling limitations of different spatial datasets to be directly compared.

iv. Comparing Scale Domains of Various Spatial Datasets

With the exception of studies performed by Gilbert (1989), Rees (1992), and Bian Walsh (1993), most research has focused on identifying the scaling limitations (i.e. scale domains and thresholds) for a single spatial dataset and has demonstrated little interest in how domains differ between datasets for a common geographical area.

Identifying the scale domains for differing spatial variables is critical for properly integrating them in models. That is, in theory, only datasets sharing a common scale or common scale domain can be combined in models. Therefore, the scaling limitations of each spatial dataset (scale domains and thresholds) should be identified and compared to ensure the integrity of the model.

v. Implementation and Dissemination of Scaling Information

Considering the large number of individuals currently utilizing spatial data, the need for scaling-up data, and the proportion of users unaware of the effects and impacts of scaling data, it is imperative that researchers begin broadly disseminating information regarding the limitations and effects of scaling spatial data. Distribution of such information should help curtail the current level of data misuse and misapplication.

Although results may vary between each of the techniques currently used to identify scaling limitations, each approach suggests that scale domains and thresholds do exist. As a result, users will begin to recognize that data is not infinitely scalable and, subsequently, improve their methods of manipulating spatial data.

Distributing scaling information and the techniques used for identifying the scaling limitations of spatial data could eventually make calculating scaling information easier. The information to be distributed could be attached to spatial data (or, embedded in digital data) to prevent the extension of information between dissimilar domains and the errors that would inevitably result.

Undoubtedly, the best way to prevent any attempts to scale data beyond its threshold would be to have the computation of scaling limitation data done automatically by the analytical software. Automating the procedures would prevent the general user from being able to bypass, ignore or forget the scaling limitations of the data. As a result, the integrity of spatial research, as a whole, would improve.

XI. Conclusion

Scale is a fundamental component of all research. Whether it is implicitly or explicitly recognized, scale affects all observations, interpretations, and subsequent decisions. The effects of scale on the interpretation of spatial phenomena have been

recognized for some time by geographers, but not until recently has there been a concentrated effort to address these issues.

The scale problem is essentially a combination of many interrelated problems that are linked together in a 'web-like' fashion. This 'web' of problems results in the cyclical, chaotic, and non-linear character of the overall problem. The complexity demands research to be very specific and, as a result, solutions produced for one component of the problem do not promote solutions to the others. In fact, the solution for one component quite often increases the complexity of others. Essentially, the scale problem is a system unto itself in that it follows Newton's third law which states that for "every action there is an equal and opposite reaction."

Like the scale problem, scaling is also a very complex issue. Scaling is not a simple process of integrating, aggregating or disaggregating spatial values at one hierarchical level to estimate phenomena at broader or finer spatial scales. Rather, scaling is the transcending of concepts between different levels of space (and time). Scaling requires the identification of the major factors operational at each scale of observation, their relationship with those operating on the scales above and below, and the constraints and feedback on those factors (Caldwell et al., 1993; van Gardingen et al., 1997).

The increasing demand to scale (link data across spatial scales) has emphasized the need to identify the effects of scale on spatial data. The main focus of current research has been on identifying the appropriate scale at which to study spatial phenomena and on defining the scaling limitations of spatial datasets. Despite the considerable amount of research performed in this area, more is required in order to produce viable methods for scaling spatial data. In fact, considering the nature of the problem and the related issues such as the modifiable areal unit problem, the uniqueness of place, and the unavoidable errors associated with sampling and statistics, the need for further research is tremendous.

Considering its magnitude and complexity, it may be impossible to truly solve the scale problem. However, despite that possibility, the scale problem still deserves further research. The theoretical and practical natures of the scale problem have been recognized but further philosophical and empirical treatments are required.

It has been suggested that guidelines for scaling spatial data need to be developed. As well, the development of new and the refinement of existing scaling technologies have also been identified as areas where more future work is required. Although it is recognized that they might not produce the ultimate solutions to the scale and scaling problems, innovative technologies and approaches will definitely contribute to the progress of scaling spatial data, and will continue to contribute with further advances.

At the very least, the development of new technologies and theories will serve to increase the current level of awareness regarding the effects of scale on spatial research. And, sometimes awareness of such effects is just as important as solutions to them. What is important is that investigations continue to probe for that ultimate answer to the problem of scale; allowing stagnation or apathy to seep into normally inquisitive minds would be detrimental. The fact that there may not be an answer to this problem should not be viewed as a roadblock or dead end. Rather, it should be viewed as a challenge, as the catalyst that will ignite inquiring minds.

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Appendix H: An Internet Map Server in Support of Climate Change Impacts and Adaptation Research

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Abstract

The Prairie Adaptation Research Collaborative (PARC) facilitates interdisciplinary research on adaptation to the impacts of climate change in the prairie provinces. The goal of the PARC research program is to contribute to the development of public policy to minimize the possible negative impacts of climate change and to take advantage of new economic and environmental opportunities that may arise. The research also contributes to adaptation strategies that have practical application to decision making.

In support of PARC's mandate, we have implemented an Internet Map Server (IMS) at the PARC web site (www.parc.ca) to 1) report status and trends relative to climate change impacts and adaptation, and 2) address data, information and knowledge management within the PARC network of researchers and partners. The web site is intended as a platform for sharing information and encouraging discussion of climate change impacts and adaptation. The IMS enables scientists and stakeholders to apply simple climate change scenarios to geo-referenced biophysical and social data, and dynamically create maps that display the geographic distribution of potential impacts of climate change. With a limited capacity for spatial analysis, most geoprocessing and the climate impact modeling is done offline within a GIS environment. The IMS will serve the output from climate impact models, such that the model results can be customized by the web site user and be most readily applied to the discussion and analysis of adaptation strategies.

The Prairie Adaptation Research Collaborative

The 1998 Option Paper for Science, Impacts and Adaptation (Canadian Climate Program Board, 1998) proposed a nation-wide Canadian Climate Impacts and Adaptation Research Network (C-CIARN) with an initial node to be established in an region where the effects of climate are significant and where some adaptation research capacity already exists. The Canadian Climate Centre's general circulation model predicts that the largest CO_2-induced rise in mean surface temperature in southern Canada will occur in the western interior (Boer et al. 1999). Most GCMs also forecast reduced net soil moisture and water resources in summer (Herrington et al., 1997). A common climate change scenario also suggests more frequent extreme conditions including drought and major hydroclimatic events (Hengeveld, 2000). Instrumental records for the prairie provinces show statistically significant trends in various climate variables (Akinremi, et al., 1999; Cutforth, et al.. 1999; Zhang et al., 2000).

In the Prairies, the agricultural community has a history of adapting to climatic variability. The level of agricultural adaptation effort already resident in the Prairie Farm Rehabilitation Administration (PFRA), and the supporting research activities of the Research Branch of Agriculture and Agri-food Canada at its research stations across the Prairies, made Regina the logical base for pursuing climate impacts and adaptation research. The federal government therefore committed in mid 1999 to building upon this base by establishing the Prairie Adaptation Research Collaborative (PARC). PARC supports interdisciplinary research on adaptation to the impacts of climate change on the Prairies. It coordinates and encourages collaborative research among sectors and disciplines, and, through the training of new graduates, acts as a focal point for the professional development of researchers in this emerging field of study. The objective of the research activities is to support programs and policy that attempt to minimize the possible negative impacts of climate change and to take advantage of new economic or environmental opportunities that may arise. Research supported by PARC examines the climatic sensitivity of agriculture, forestry, water resources and other sectors. It assists in developing adaptation strategies that have practical applications to decision making. In support of its mandate, PARC implemented an Internet Map Server (IMS) to 1) report status and trends relative to climate change impacts and adaptation, and 2) address data, information and knowledge management within the PARC network of researchers and partners.

The PARC IMS

The PARC web site (www.parc.ca) is intended as a platform for sharing information and encouraging discussion of climate change impacts and adaptation. The IMS enables sharing of geo-referenced data and discussion based on the spatially-explicit assessment of climate change impacts and adaptation strategies. It supports various applications of geographic analyses of climate impacts and adaptation. The map services are a geographic user interface for capturing time series data by location, for example, stream flow records by watershed (Figure 1). The IMS is a portal for the distribution of spatial data sets, such that a common spatial framework, such as ecological land classification (Figure 2), is in use throughout the PARC network of scientists and policy makers. A spatial data directory, including metadata files, facilitates the acquisition of georeferenced data via the PARC web site. Many of the 32 research projects, funded by PARC during 2000-01, were GIS-based. The reporting of these projects at the PARC web site will include serving the georeferenced results. The most advanced application of the IMS is the crude modeling of potential impacts of climate change. Researchers and stakeholders can apply simple climate change scenarios to geo-referenced biophysical and social data. With the IMS's limited capacity for spatial analysis, most geoprocessing and the climate impact modeling is done offline within a full-featured GIS environment. The IMS, however, is able serve the output from climate impact models, such that the model results can be customized by the web site user and be most readily applied to the discussion and analysis of adaptation strategies.

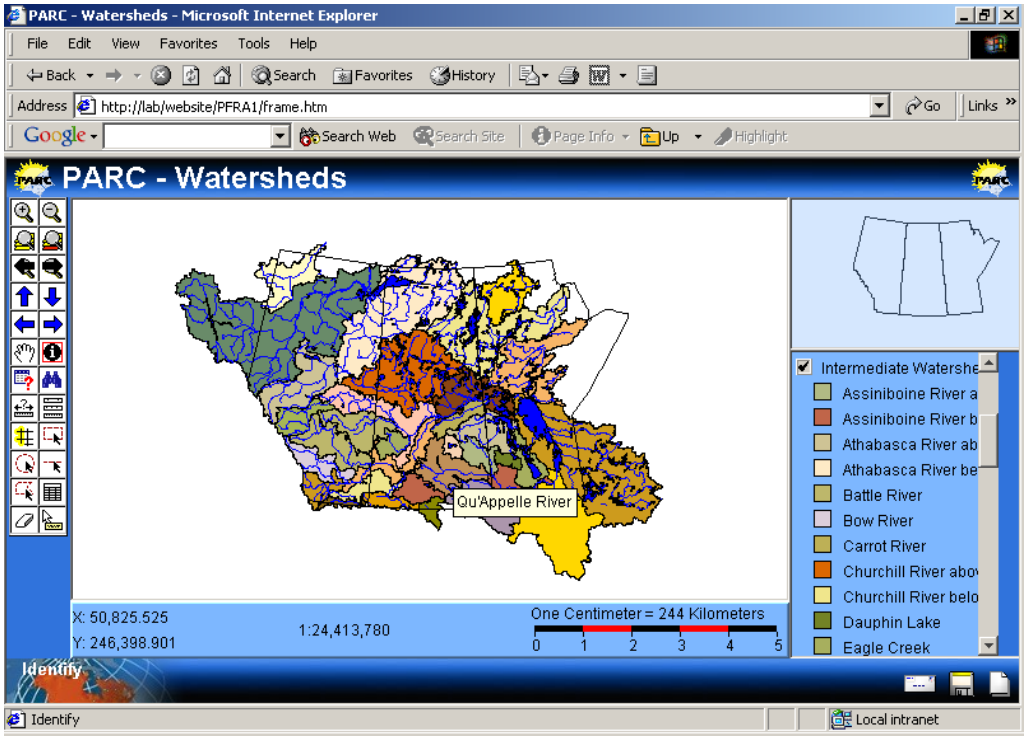

Figure 1. Watersheds of the Prairie Provinces: The user can select a layer that gives the locations of hydrometric stations and, using the IMS tools, summary data.

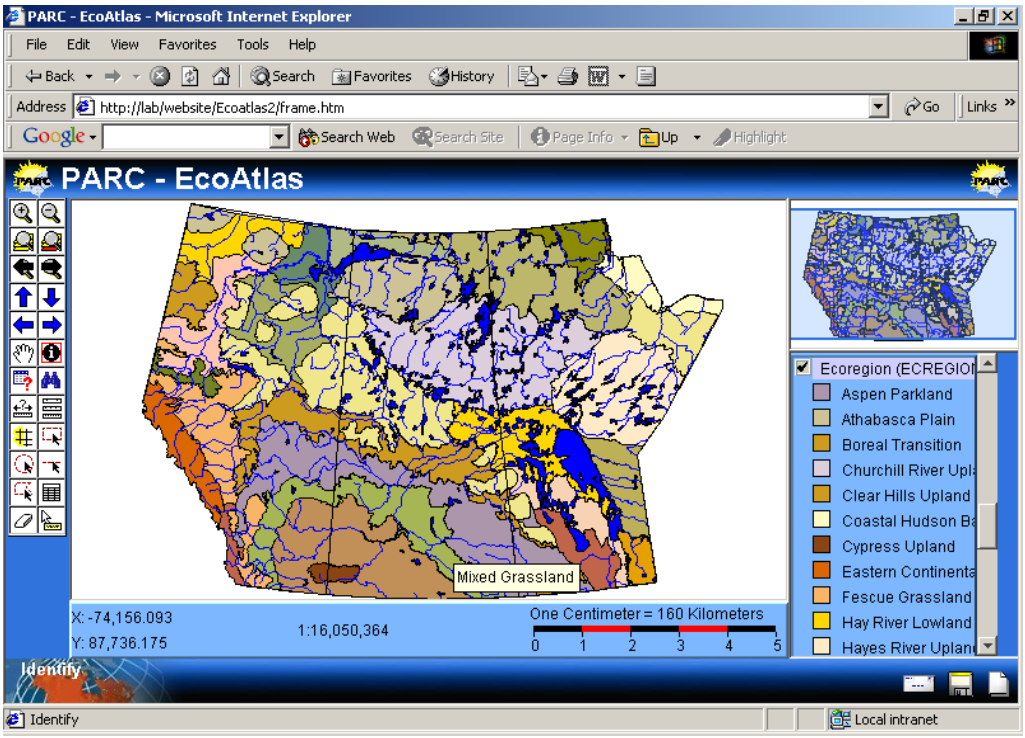

Figure 2. Ecoregions of the Prairie Provinces: A common geographic framework for the studies of climate change impacts and adaptation.

Spatial Analysis in ArcIMS

Map services created in ArcIMS can be analyzed two different ways: directly through the web browser or through Arc Explorer, a map viewer that is provided free of charge by ESRI. The analyses of spatial data through the web browser requires a one-time download of a Java Viewer that provides the user with the ability to interact with on-line map services. The Java Viewer has a variety of tools that allows the user to manipulate and query the map services. The map manipulation tools enable users to change the view of the map service by zooming, panning and changing the map units. There are also various querying tools that allow for the identification, measuring, buffering, selection and querying of the individual layers in a map service (Figure 3). The ability to query attribute data in ArcIMS enables the user to perform simple attribute analysis on the different layers in a map service. The query builder in ArcIMS allows for the users to select an individual map layer, query for several different attributes at the same time and can produce simple statistics based upon the query. This allows for a limited spatial analysis of the information contained in the map services.

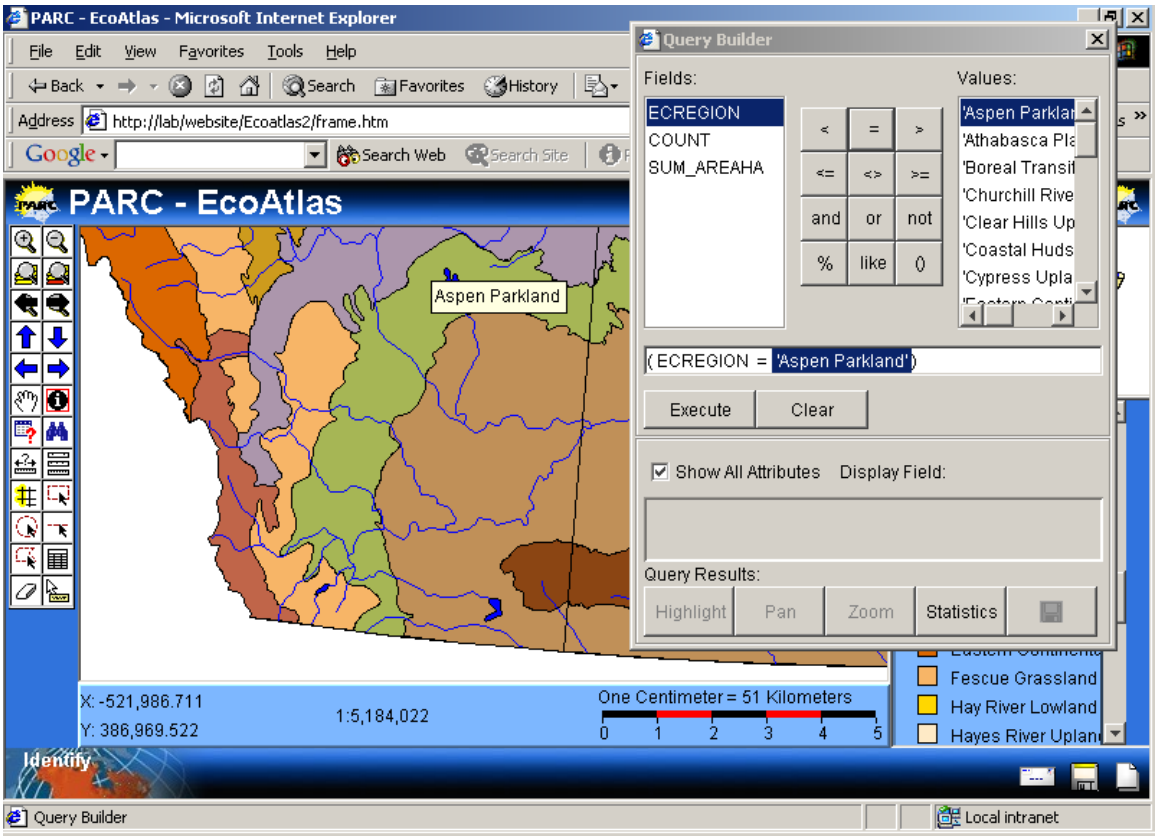

Figure 3. An example of spatial analysis by building a query based on the attributes of ecoregions.

Limitations of Spatial Analysis in ArcIMS

While both ArcIMS and ArcExplorer allow the user to directly interact and query map services, spatial analysis is limited to the querying of a single layer in a map service. In addition, ArcIMS does not allow for the use of continuous data such as grids. Grids can only be represented as static images. The lack of geoprocessing capabilities and the inability to process continuous data, such as most climate related data, constrains our use of ArcIMS for online spatial modelling. However, it is still possible to model spatial phenomena using the present capabilities of ArcIMS. The simplest approach is to create a series of map layers that represent changes in the model variables. This allows the user to view and query predefined outcomes of a model. Online modeling requires that the user interactively change the variables in a model, which in turn is reflected in the map layer. Since querying in ArcIMS is limited to single map layers, a database containing all the model variables must be created offline by overlaying ('union') polygon coverages representing the variables. Using this new layer in an ArcIMS map service, the user can build queries according various model parameters, thereby mapping matching map units. This "one layer" approach to spatial modelling in ArcIMS applies only to discrete data. This necessitates the transformation of continuous data and model structures, affecting the outcome of modeling. The resolution of polygons and their discrete nature are not conducive to accurately representing continuous geographic phenomena. Another problem with the use of the discrete "one layer" modelling is the proliferation of polygons by the overlay process. The number of polygons and variables has determines the time required to serve and query the spatial model. New generations of IMS technology will undoubtedly address these limitations.

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