PROJECT REPORT
2000-33
INTERIM PROJECT REPORT

sustainable
forest
management
network

réseau
sur la
gestion durable
des forêts

Ecosite Mapping and Dendroclimatology Duck Mountains, West Central Manitoba

A Network of Centres of Excellence
Un réseau de centres d'excellence

D.J. Sauchyn

For copies of this or other SFM publications contact:

Sustainable Forest Management Network
G208 Biological Sciences Building
University of Alberta
Edmonton, Alberta, T6G 2E9
Ph: (780) 492 6659
Fax: (780) 492 8160
http://www.ualberta.ca/sfm/

ISBN 1-55261-093-4

Ecosite Mapping and Dendroclimatology

Duck Mountains, West Central Manitoba

SFM Network Project: Historical Disturbance Regime,
FML #3, West Central Manitoba

by

Dr. D.J. Sauchyn, Professor
Department of Geography
University of Regina

September 2000

ABSTRACT

The objective of our SFMN project is to contribute to an understanding of the historic disturbance regime of FML #3 in the Duck Mountains of west-central Manitoba through the digital mapping of forest ecosites and the spatial analysis of physical controls (landform, drainage, local climate) on the distribution of forest ecosystems. Understanding the control of disturbance on forest structure, and emulating natural disturbance through forestry practices, requires a regional and historic perspectives on the distributions of disturbance, climate and forest ecosystems. The integration of climate records with digital map (GIS) data is the basis for linking the forest geography and natural history and, thereby, comparing patterns of forest management and natural disturbance.

Our ecosite classification and digital date base is a high resolution spatial model of the forest ecosystems and a framework for scaling up models of biophysical processes and associated ecological data. An assemblage of ecosites is the geographic expression of biophysical activity over time scales which are longer than the diurnal and seasonal variability of ecological processes and closer to the time frame for forest management and planning. The distribution of the forest ecosystems of FML #3 reflects the interaction of topography, drainage, natural disturbance and human activities. There are steep gradients in soil moisture with relatively subtle changes in elevation and slope, and thus much local variability in forest vegetation. Despite this physical control on the distribution of boreal forest ecosystems, there are few SFMN studies at the landscape (regional) scale. Our digital and spatial ecosite data base will support forest management planning with data at appropriate spatial and temporal scales.

ACKNOWLEDGEMENT

This project has been assisted to a great degree by the industry partner, Louisiana Pacific Limited. This assistance has included considerable in-kind contributions of digital geographic data and logistical support in the field. During May-June 2000, the field crew was able to use the facilities of the Mixed Wood Forest Research Centre at Wellman Lake. The ecosite classification and mapping described here is the masters thesis research of Trevor Hadwen. Advice on the remote sensing aspects of this study has been provided by Dr. Brad Wilson, Lakehead University, Dr. Ron Hall, Canadian Forest Service, and Dr. Gerardo-Arturo Sanchez-Azofeifa, University of Alberta. The field and laboratory assistants have been Kevin Whittmire, Nathan Richea, Antoine Berault, Jason Tuchelt and Jennifer Stroich.

INTRODUCTION

A major theme of the SFM-NCE is documenting natural disturbance regimes of the southern boreal forest relative to current forestry practices. Understanding the control of disturbance on forest structure and emulating natural disturbance through forestry practices requires a regional and historic perspectives on the distributions of disturbance, climate and forest ecosystems. The project objective is to contribute to an understanding of the historic disturbance regime of FML #3 in the Duck Mountains of west-central Manitoba (Figure 1) through the digital mapping of forest ecosites and the spatial analysis of physical controls (landform, drainage, local climate) on the distribution of forest ecosystems. The integration of climate records with digital map (GIS) data is the basis for linking the forest geography and natural history and, thereby, comparing patterns of forest management and natural disturbance.

While forest inventory maps exist for FML #3, the map units represent stand age structure and composition and thus a variety of environmental controls on the distribution of forest ecosystems. We are constructing a higher-resolution spatial model of the forest mosaic by combining classified satellite imagery with digital soil and topographic data. At this ecosite scale, forest boundaries and patterns tend to reflect natural disturbance and physical factors. The digital ecosite database will be used, with other historical (archival) and digital geographic (forest inventory, geology, soils) data, to address the relationship between human activities, including forest management practices, and the natural disturbance regime.

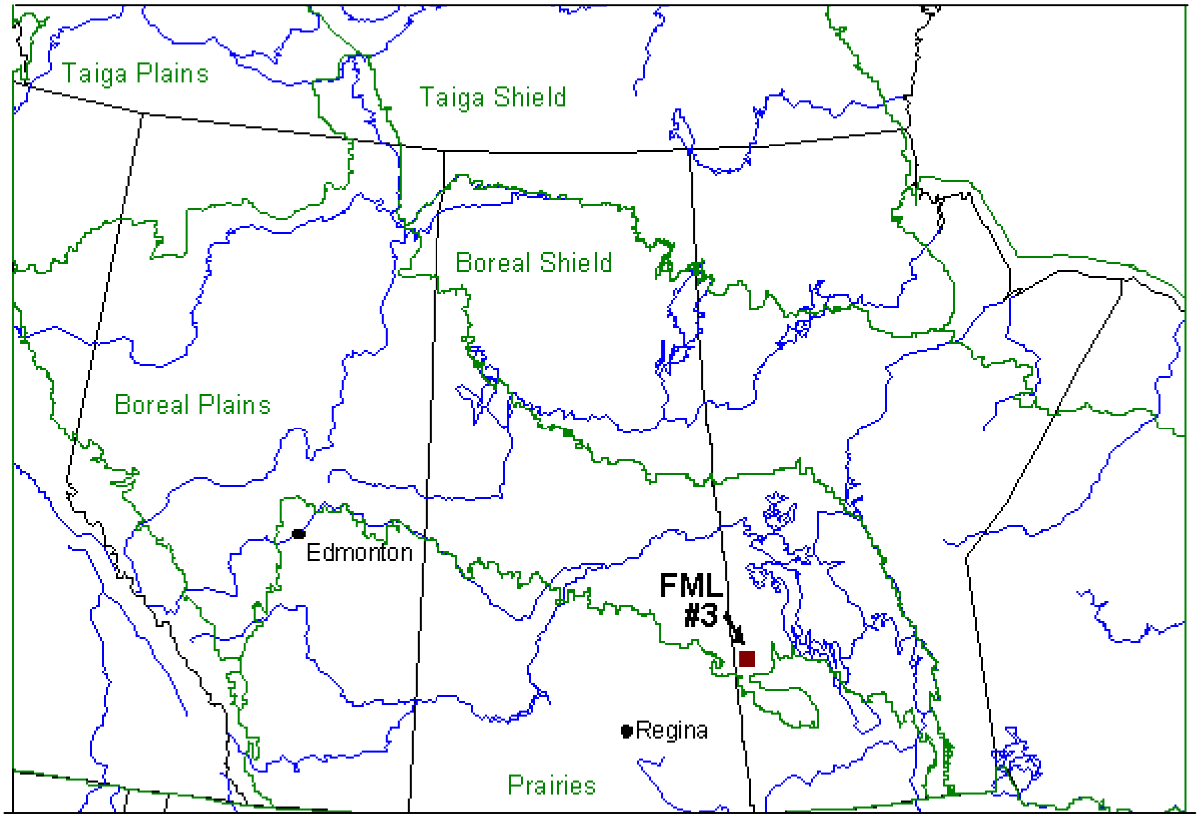

Figure 1. The location of FML #3 in the Boreal Plains Ecozone and west-central Manitoba.

SUMMARY OF DATA ANALYSIS

The research objectives have been achieved through a combination of field data collection and spatial analysis of the forest ecosystem using GIS and remote sensing. Using the ArcInfo GIS and EasiPace image analysis system at the University of Regina, we have mapped the forest ecosystems of FML #3 based on a ecosite classification. The data base includes detailed field surveys more than 200 forest ecosites, classified satellite imagery, and digital geographic data supplied by Louisiana Pacific Limited. The field description of one ecosite is given in Appendix A. Analysis of these data is focused on the control of topography, soil and drainage on local variability in the forest ecosystems. Scale is a major theme in the mapping and interpretation of forest structure and disturbance. We have been careful to define the spatial scope of our study as corresponding tot he ecosite scale. Our research on the scale factor in disturbance studies resulted in a manuscript on the spatial modeling of disturbance. This manuscript has been accepted for publication in a special issue of the Journal of Environmental Monitoring and Assessment. It appears in this report as Appendix B.

In conjunction with the surveying of ecosites, tree cores have been collected to establish forest age structure. The tree ring data serve other purposes related to our study. A master chronology of regional tree ring width variation is the basis for assigning calendar years to the rings of dead wood (floating chronologies) extending our temporal perspective on the annual climate and tree growth. The ring width variation is a record of climatic variability. Given the strong links between weather and disturbance, the reconstruction of annual climate from standardized ring widths is a the major aspect of our study of the regional climate. The statistical relationship between standardized ring widths from *Pinus banksianna* (jack pine) and instrumental precipitation records from Environment Canada is the basis for our reconstruction of August-July precipitation for the period 1831-1999 (Figure 2). These data were included in a poster presentation at the International Conference on Dendrochronology for the Third Millennium, Mendoza, Argentina, April 2-7, 2000.

Our research has involved frequent interaction with other SFMN researchers and participation in various network activities. Trevor Hadwen attended the SFM Network Forestry Field Camp at Hinton, Alberta, during November 4-6 and then spent a few subsequent days on an SFMN exchange in the remote sensing laboratory of Dr. Arturo Sanchez-Azofeifa at the University of Alberta. We have attended various meetings of the Manitoba node of the SFMN in Swan River and Winnipeg. We have co-ordinated our field surveys with activities of the industry partner and other network researchers working in the Duck Mountains, in particular, the graduate and research assistants working under the supervision of Dr. Norm Kenkall of the University of Manitoba

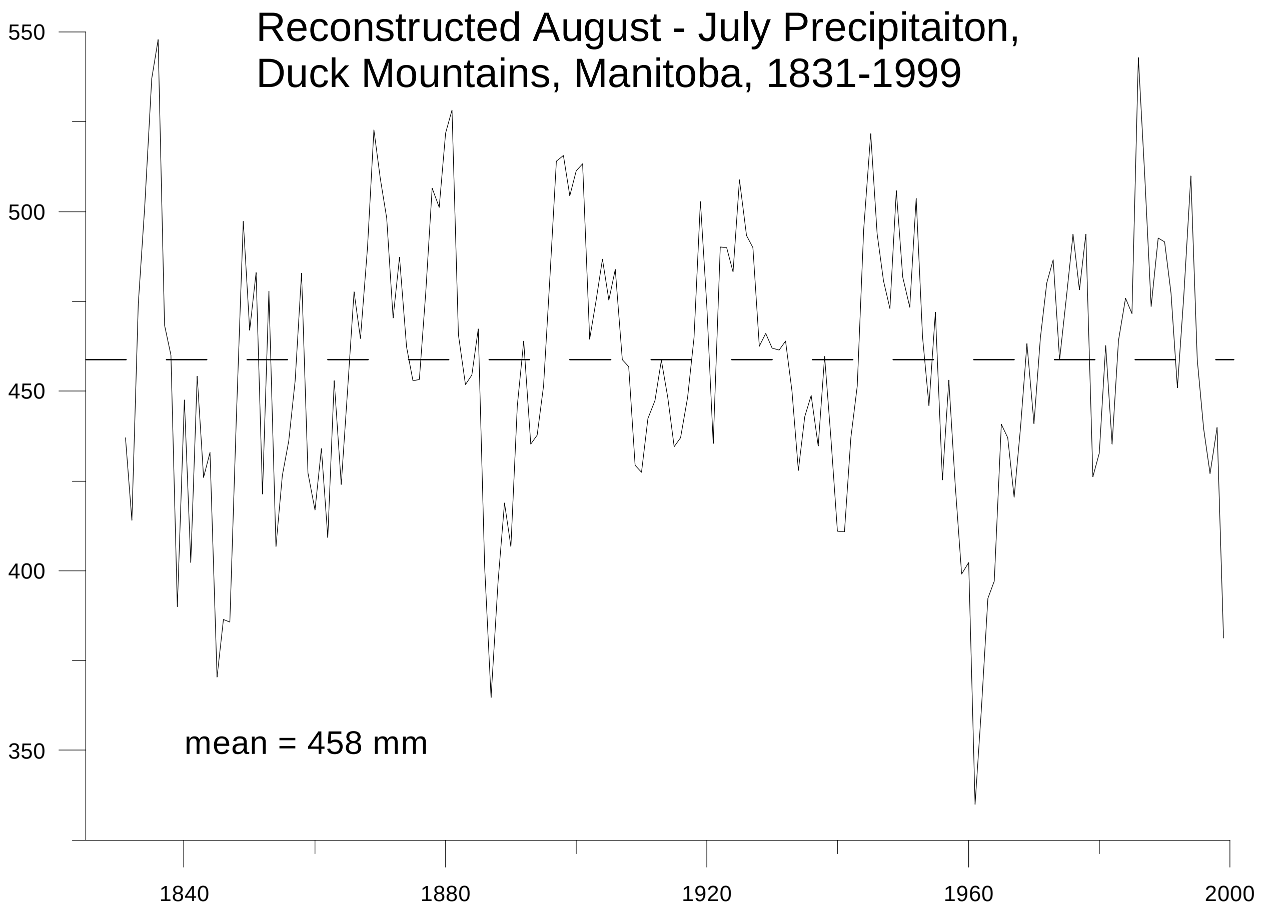

Figure 2. August - July precipitation reconstructed from the growth rings of *Pinus banksianna* (jack pine).

MANAGMENT APPLICATIONS

Our digital ecosite database and corresponding digital maps represent a spatial framework for sustainable forest management planning and the interpretation of research at other scales, in particular, studies of stand dynamics. Therefore the development and delivery of our database is in consultation with Louisiana-Pacific (L-P) and SFMN researchers. We are working with L-P staff to implement the project deliverables, in particular, the GIS-based products.

Whereas ecological processes operate locally, and thus require the monitoring of organisms and communities, forest ecosystems are managed at a coarser scale. Thus an ecosite classification and digital maps are a framework for the scaling up of biophysical processes and associated ecological data. An assemblage of ecosites is the geographic expression of biophysical activity over time scales which are longer than the diurnal and seasonal variability of ecological processes and closer to the time frame for forest management and planning.

CONCLUSIONS

The distribution of the forest ecosystems of FML #3 reflects the interaction of topography, drainage, natural disturbance and human activities. The geomorphology and surficial geology of the Duck Mountains are typical of the southern boreal forest, in terms of the impact of continental glaciation on the geography of soil (parent materials), wetlands, lakes and streams. There are steep gradients in soil moisture with relatively subtle changes in elevation and slope, and thus much local variability in forest vegetation. Landform and drainage also influence susceptibility to natural disturbance, especially fire. Despite these physical controls on boreal forest ecosystems, discussions with co-investigators in SFMN Legacy 1 suggest that research has not been initiated at the landscape (regional) scale to examine relationships among landform, surficial materials, drainage and the spatial variability of boreal forest ecosystems. Our digital and spatial ecosite data base will enable researchers and forest managers to examine these relationships and will support forest management planning with data at appropriate spatial and temporal scales.

REFERENCES

Last, W.M. and Sauchyn, D.J. 1993. Mineralogy and lithostratigraphy of Harris Lake, southwestern Saskatchewan, Canada. *Journal of Paleolimnology*, 9: 23-29.

Porter, S.C., Sauchyn, D.J. and Delorme, L.D. In press. The Ostracode Record from Harris Lake, southwestern Saskatchewan: 9200 years of local environmental change. *Journal of Paleolimnology*.

Sauchyn, D.J. 1993 *Quaternary and Late Tertiary Landscapes of Southwestern Saskatchewan and Adjacent Areas*. Canadian Plains Research Center, Regina.

Sauchyn, D.J. 1997. Practical and theoretical basis for mapping landscape sensitivity in the southern Canadian Interior Plains. *Transactions of the Kansas Academy of Science*, 100(1-2): 61-72.

Sauchyn, D. J. and Beaudoin, A. B. In press. Recent Environmental Change in The Southern Canadian Plains. *Canadian Geographer*.

Sauchyn, D.J. and Porter, S.C. 1992. *Pre-Settlement Precipitation Variability in southeastern Alberta and southwestern Saskatchewan*. Final Report to the Prairie Farm Rehabilitation Administration on An Environmental Sustainability Initiative Project.

Sauchyn, M.A. and Sauchyn, D.J. 1991. A Continuous record of Holocene pollen from Harris Lake, Southwestern Saskatchewan, Canada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 88: 13-23.

Schweingruber, F.H. 1989. *Tree Rings: Basics and Applications of Dendrochronology*. Kluwer Academic Publishers, Dordrecht, 276 pp.

Stokes, M.A. and Smiley, T.L. 1968. *An Introduction to Tree-Ring Dating*. University of Arizona Press, Tucson, 73 pp.

Appendix A: **Ecological Land Classification, Field Sheet - Duck Mountain, MB**

Plot ID: 121

Location:
Lower end of northern escarpment along highway

Date: Aug 3/99
Time: 3:00pm
Slope: 4-6 degrees

Aspect: 30 degrees
Elevation: 457m

GPS UTM Coordinate:

- GPS II: 0360204
5760787

- Waypoint: 119

Air Photo #: 86

Photo Roll #: Canon 3

Photo: # 9, 10 - Understory
11 - Canopy

Dominate Canopy Vegetation
TA10

Dominate Understory Vegetation
Beaked Hazelnut, Green Alder, Mountain Maple

Vegetation Type **(Field):** V5 Aspen Hardwood
(Lab): V5 Aspen Hardwood

Ecosite Type **(Field):** d2 low-bush cranberry
(Lab): d2 low-bush cranberry

Site Description:

- Located at the Bottom of the Northern Escarpment Along the highway.
- 100% Trembling Aspen canopy
- Very dense high shrubs content including Beaked Hazelnut, Green Alder, Mountain Maple
- High-bush Cranberry and Dogwood also present in lower amounts
- Dominate understory species include Canada Western Violet, Kidney Violet, Woodland Strawberry, wintergreen and Northern Bedstraw.
- Uncovered leaf litter is approx. 50%
- Very thick Canopy and dense shrub cover (canopy at 3m close to 90% closure)
- Little light reaching the canopy floor

Crown Closure Estimate:

a) A (6-30%) [✓ b) B (31-50%)] c) C (51-70%) d) D (71-100%)

Dominate Tree Species (Canopy):

a) Pine [✓ b) Aspen] c) Birch d) White Spruce e) Fir f) Black Spruce g) Tamarack h) Non Forested

Stand Origin:

Minimum: **Maximum:** **Average:** **Comments: No cores taken, TA Mature**

Topo-Position:	**Surface Shape**	**Micro Topography**	**Moisture Regime**
a) Crest	a) Concave	[✓ a) Smooth]	a) Very Xeric (Extremely Dry)
b) Upper Slope	b) Convex	b) Micro Mounded	b) Xeric (Dry)
c) Middle Slope	[✓ c) Straight]	c) Slightly Mounded	[✓ c) Mesic (Moist)]
d) Lower Slope		d) Strongly Mounded	d) Hygric (Wet)
[✓ e) Toe]		e) Extremely Mounded	e) Hydric (water at/near surface)
f) Depression			

Canopy Composition: **Plot #121**

Main Canopy: TA

Understory Trees > 5m: **TA**

Understory Trees < 5m: **Mountain Maple 5m tall dense canopy**

Tree #	Species	DBH (cm)	Heights (m)	Ht to Live	Story	Age	Comments
1	TA	20.4	20	10	M		
2	TA	14.0	20	8.5	M		
3	TA	16.2	10.5	7.5	M		
4	TA	50.9	24	12	O		Fungus growth, decay present
5	TA	59.9	23	12	O		
6	TA	17.1	12.5	8	M		
7	TA	17.0	12.5	8	M		
8	TA	47.2	25	13	O		
9	TA	15.8	11	7	M		
10	TA	17.0	13	9	M		
11	TA	8.7	9	7	M		
12	TA	57.2	23	12	M		
13	TA	58.4	24	12	M		
14	TA	18.9	12.5	9	M		
15							
16							
17							
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							
29							
30							
31							

Understory Species Composition   Plot   #121

	% Cover	Comments
Bare Soil / Rock	0	
Dead Fall	2-3	
Leaf Litter	50-60	Large areas of leaf litter with no vegetation cover

Tall Shrubs	% Cover	Comments
Mountain Maple	50	
Beaked Hazelnut	30	
High-bush Cranberry	10	

Low Shrub	% Cover	Comments
Aspen Suckers	3	
Choke Cherry	2	
Low-bush Cranberry	2	
Pincherry	1	
Snow Berry	2	
Saskatoon	3	
Rose	1	
Dogwood	2	General area contains more dogwood (5%)

Forbs	% Cover	Comments
Sweet scented bedstraw	2-3	
Dewberry	2	
Strawberry	3	
Bishops cap	5	
Lindley’s aster	5	
Kidney Violet	3	
Canada western violet	5-7	
Red and white baneberry	3	
Coltsfoot	1	
Starflower	1-2	
Cinquefoil	1-2	
Wild lily of the valley	2-3	
Bluebell	2-3	
Bracken Fern	2	
Wild sarsaparilla	2	
Starflower Solomon Seal	1-2	
Northern bedstraw	1	

Mosses	% Cover	Comments
Un-Identified	< 1	Small amount of moss on rotting wood

Grasses	% Cover	Comments
Rough- leaved mountain rice	< 1	

Soil Conditions: Plot #121

Organic Matter Thickness	3 cm – Very thin Mainly well decomposed, with the exception of the leaf litter on the surface
Humus Form	Ah – 15-17cm – mixing of Organics and mineral soils. Transition – dark on top lighter at deeper depths.
A Horizon Thickness	3-60cm Sandy Loam 60-70cm Sandy (extremely sandy)
Surface Texture	Organic
Effective Texture	Sandy Loam
Mottles	None Present at depths to 1m
Gley	None Present at depths to 1m
Coarse Fragment	No real large coarse fragments. Some coarse sands and very small gravels occur throughout the pit

Soil Pit Dug: [✓ Yes] / No **Pit Dug at Position -** NW NE SE SW [✓ Middle]

Samples Taken: **A: 25 cm** **B: 85 cm** **C:N/A cm**

Profile Sketch

Drainage: Well

Depth to ground Water: [✓ Unknown] **/** **cm**

Standing Water: **Present / [✓ Absent]**

Comments:
- Very Dry Soils
- Rich
- Large sand content at depths of 85-90 cm
-

Humus	A Horizon	Soil Texture	Soil Depth	Coarse Fragments	PH	Seepage	Nutrient Regime
[✓ Mor]	Ae Hor Present	Coarse	Extremely Shallow	a) High	Acidic	Present	Very Poor
Moder	A Hor. Absent	[✓ Medium/fine]	[✓ Shallow to Deep]	- Sandy Soils	[✓ Neutral]	[✓ Absent]	Poor
Mull	Ah Hor. Present			>35 %	Alkaline		Medium
				- Loamy Soils			[✓ Rich]
				>70 %			Very Rich
				[✓ b) Low to Interm]			

Appendix B

MODELING THE HYDROCLIMATIC DISTURBANCE OF SOIL LANDSCAPES IN THE SOUTHERN CANADIAN PLAINS: THE PROBLEMS OF SCALE AND PLACE

D.J. (DAVE) SAUCHYN

Department of Geography, University of Regina

Regina, Saskatchewan, Canada S4S 0A2

Accpeted for publication in *Journal of Environmental Monitoring and Assessment*

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.

Acknowledgments

The crafting of this paper was greatly assisted by constructive criticism from Dirk de Boer, Don Lemmen and Dan Muhs. Funded was provided by EMAN and the Geological Survey of Canada (Palliser Triangle Global Change Project).

References

Allen, T.F.H. & Starr, T.B. 1982. Hierarchy; perspectives in ecological complexity. University of Chicago Press, Chicago.

Baker, V.R. & Twidale, C.R. 1991. The reenchantment of geomorphology. Geomorphology, 4: 73-100.

Bass, B., Akkur, N., Russo, J., & Zack, J. 1996. Modelling the biospheric aspects of the hydrological cycle. In: Regional Hydrological Response to Climate Change, edited by J.A.A. Jones, *et al*., Kluwer Academic Publishers, the Netherlands.

Boer, G.J., McFarlane, N.A. & Lazare, M.. 1992. Greenhouse gas-induced climate change simulated with the second generation general circulation model. Journal of Climate 5(10): 1045-1077.

Broecker, W. 1997. Will our ride into the greenhouse future be a smooth one? GSA Today, 7(5): 1-7.

Broecker, W.S. 1994. Is Earth Climate Poised to Jump Again? Geotimes, 39(11):16-18.

Brunsden, D. 1993. Barrier to Geomorphological Change. In D.S.G. Thomas & R.J. Allison (eds), Landscape *Sensitivity*: 7-12. Chichester: Wiley.

Brunsden, D. & Thornes, J.B. 1979. Landscape sensitivity and change. *Transactions, Institute of British Geographers* 4(4): 463-484.

Bull, W.B. 1991. Geomorphic Responses to Climatic Change. New York, Oxford University Press. 326 pp.

Buol, S.W., Hole, F.D., & McCracken, R.J., 1980. Soil Genesis and Classification. Iowa State University Press, Ames.

Church, M. 1996. Space, time and the mountain - how do we order what we see? In: The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology, edited by B.L. Rhoads & C.E. Thorn, John Wiley & Sons, p. 147-170.

de Boer, D.H. 1992. Hierarchies and spatial scale in process geomorphology: a review. Geomorphology, 4: 303-318.

Drury, W.H. & Nisbet, I.C.T. 1971. Inter-relations between developmental models in geomorphology, plant ecology, and animal ecology. General Systems, XVI: 57-68.

Expert Committee on Soil Survey. 1987. The Canadian System of Soil Classification, 2nd ed. Agriculture Canada Publication 1646, 164 pp. Supply and Services Canada, Ottawa.

Government of Canada (1997). Canada's Second National Report on Climate Change. Ottawa. (http://www1.ec.gc.ca/cgi-bin/foliocgi.exe/climate_e/toc?)

Haigh, M.J. 1987. The holon: Hierarchy theory and landscape research. In “Geomorphological Models – Theoretical and Empirical Aspects”. F. Ahnert, ed., Catena Supplement 10: 181-192.

Haff, P. 1996. Limitations on predictive modeling in geomorphology. In: The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology, edited by B.L. Rhoads & C.E. Thorn, John Wiley & Sons, p. 337-358.

Harvey, D.W. 1968. Pattern, process, and the scale problem in geographical research. Transactions, Institute of British Geographers, 45: 71-78.

Herrington, R., Johnson, B. & Hunter, F. 1997. Responding to Global Climate Change in the Prairies – Volume III of the Canada Country Study: Climate Impacts and Adaptation. Environment Canada. Regina, Saskatchewan.

Hoekstra, T.W., Allen, T.F.H., & Flather, C.H. 1991. Implicit Scaling in ecological research. Bioscience, 41(3): 148-154.

Hole, F.D. 1978. An approach to landscape analysis with emphasis on soils. Geoderma, 21: 1023.

Hole, F.D. & Campbell, J.B. 1985. Soil Landscape Analysis. Routledge & Kegan Paul, London, 196 p.

Hostetler, S. W. 1994. Hydrologic and Atmospheric Models: The (Continuing) Problem of Discordant Scales. An Editorial Comment. Climatic Change, 27: 345.

Hostetler, S.W. & Giorgi, F. 1993. Use of Output From High-Resolution Atmospheric Models in Landscape-Scale Hydrologic Models: An Assessment. Water Resources Research, 29:1685-1695.

Kennedy, B.A. 1977. A question of scale? Progress in Physical Geography, 1: 154-157.

Kirkby, M.J. 1993. Long Term Interactions Between Networks and Hillslopes. In K. Beven & M.J. Kikby (eds), *Channel Network Hydrology*: Chapter 9, London: John Wiley & Sons.

Kirkby, M.J., Imeson, A.C., Bergkamp, G., & Cammeraat, L.H. 1996. Scaling up processes and models from the field plot to the watershed and regional areas. Journal of Soil and Water Conservation, 51: 391-396.

Klemes, V. 1983. Conceptualization and scale in hydrology. Journal of Hydrology, 65: 1-23.

Laprise, R., *et al*. 1998. Climate and climate change in western Canada as simulated by the Canadian regional climate model. Atmosphere-Ocean 36 2: 119-167.

Lemmen, D.S., Vance, R.E., Campbell, I.A., David, P.P., Pennock, Sauchyn, D.J., & Wolfe, S.A. Geomorphic Systems of the Palliser Triangle: Description and Response to Changing Climate; Geological Survey of Canada Bulletin 521.

Lemmen, D.S. & Vance, R.E. 1999. An overview of the Palliser Triangle Global Change Project. In: Holocene climate and environmental change in the Palliser Triangle: a geoscientific context for evaluating the impacts of climate change on the southern Canadian Prairies; edited by D.S. Lemmen & R.E. Vance; Geological Survey of Canada Bulletin 534., p. 7-22.

Levin, S.A. 1992. The problem of pattern and scale in ecology. Ecology, 7: 1943-1967.

Logan, T.J., Urban, D.R., Adams J.R. & Yaksich, S.M. 1982. Erosion control potential with conservation tillage in the Lake Erie basin: estimates using the universal soil loss equation and the land resource information system (LRIS). Journal of Soil and Water Conservation 37(1), 50-55.

Martz, L.W. & de Jong, E. 1991. Using Cesium-137 and landform classification to develop a net soil erosion budget for a small Canadian prairie watershed. Catena 18(3/4), 289-308.

Mermut, A.R., Acton, D.F. & Eilers, W.D. 1983. Estimation of Soil Erosion and Deposition by a Landscape Analysis Technique on Clay Soils in Southwestern Saskatchewan. Canadian Journal of Soil Science 63(4): 727-739.

O'Neill, R.V., DeAngelis, D.L., Waide, J.B., & Allen, T.F.H. 1986. A Hierarchical Concept of Ecosystems. Princeton University Press, Princeton, 253 pp.

Osterkamp, W.R. & Hupp, C.R. 1996. The evolution of geomorphology, ecology, and other composite sciences. In: The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology, edited by B.L. Rhoads & C.E. Thorn, John Wiley & Sons, p. 415-441.

Palliser, J. 1859. Copy of a letter from Captain Palliser to the Under-Secretary of State for the Colonies, Fort. Edmonton, Saskatchewan, May 20th, 1859. In: Papers Relative to the Exploration of British North America, Greenwood Press, New York, 1969.

Pennock, D.J. & de Jong, E. 1990. Spatial patterns of soil redistribution in boroll landscapes, southern Saskatchewan, Canada. *Soil Science* 150(6), 867-873.

Pennock, D.J., Lemmen, D.S. & de Jong, E. 1995. ^{137}Cesium-measured erosion rates for soils of five parent material groups in southern Saskatchewan. *Canadian Journal of Soil Science* 75(2): 205-210.

Phillips, J.D. 1988. The role of spatial scale in geomorphic systems. Geographical Analysis, 20: 308-317.

Phillips, J.D. 1995. Decoupling of sediment sources in large river basins. Effects of scale on interpretation of sediment and water quality. IAHS Publication Number 226, pp. 11-16.

Rhoads, B.L. & Thorn, C.E. 1993. Geomorphology as science: the role of theory. Geomorphology, 6: 287-307.

Roels, J.M. 1985. Estimation of soil loss at a regional scale based on plot measurements - some critical considerations. *Earth Surface Processes and Landforms* 10(6), 587-595.

Running, S.W., Nemani, R.R., Peterson, D.L., Band, L.E., Potts, D.F., Pierce, L.L., & Spanner, M.A. 1989. Mapping regional forest evapotranspiration and photosynthesis by coupling satellite data with ecosystem simulation. Ecology, 70(4): 1090-1101.

Saab, V. 1999. Importance of spatial scale to habitat use by breeding birds in riparian forests: A hierarchical analysis. Ecological Applications, 9: 135-151.

Salthe, S.N. 1985. Evolving hierarchical systems, their structure and representation. Columbia University Press, New York.

Sauchyn, D.J. 1993. GIS modelling of agricultural soil loss in a plains glacial landscape. *Quaternary International* 20: 163-170.

Sauchyn, D.J. 1997. Practical and theoretical basis for mapping landscape sensitivity in the southern Canadian Interior Plains. *Transactions of the Kansas Academy of Science* 100(1-2): 61-72.

Sauchyn, D.J. In press. Geoenvironmental mapping in southwestern Saskatchewan: Rainfall erosion potential. *In* Geoenvironmental Mapping: Method, Theory and Practice; edited by P. Bobrowsky, Balkema, Rotterdam.

Schumm, S.A. 1991. To Interpret the Earth: Ten ways to be wrong. Cambridge University Press, Cambridge, 133 pp.

Schumm, S.A. & Lichty, R.W. 1965. Time, Space and Causality in geomorphology. American Journal of Science, 263: 110-119.

Shields, J.A., Tarnocai, C., Valentine, K.W.G., & MacDonald, K.B. 1991. Soil landscapes of Canada: Procedures handbook and user's manual. Agriculture Canada Publication 1868/E, Minster of Supply and Services Canada, Ottawa, 74 p.

Snell, E.A. 1985. Regional targeting of potential soil erosion and nonpoint-source sediment loading. *Journal of Soil and Water Conservation* 40: 520-524.

Spedding, N. 1997. On growth and form in geomorphology. Earth Surface Processes and Landforms, 22: 261-265.

Strahler, A.N. 1952. Dynamic basis of geomorphology. Geological Society of America Bulletin, 63: 923-938.

Sugden, D.E., Summerfield, M.A., & Burt, T.P. 1997. Editorial: Linking short-term geomorphic processes to landscape evolution. Earth Surface Processes and Landforms, 22: 193-4.

Thorn, C.E. 1988. Introduction to Theoretical Geomorphology. Unwin Hyman, Boston.

Valentine, J.W. & May, C.L. 1996. Hierarchies in biology and paleontology. Paleobiology, 22: 23-33.

Vitek, J.D. & Giardino, J.R. 1993. Preface: a perspective on getting to the frontier. *In* Geomorphology: The Research Frontier and Beyond, edited by Vitek, J.D. & Giardino, J.R. Proceedings of the 24th Binghamton Symposium in Geomorphology, Hamilton, Ontario, Elsevier, Amsterdam, pp. vii-xii.

Wiken, S. A. (compiler) 1986. Terrestrial Ecozones of Canada. Ecological Land Classification Series No. 19, Environment Canada, Hull Quebec. 26pp+map

Willgoose, G., Bras, R.L., & Rodriguez-Iturbe, I. 1992. The relationship between catchment and hillslope properties: implications of a catchment evolution model. Geomorphology, 5: 21-37.

Wischmeier, W.H. & Smith, D.D. 1978. *Predicting Rainfall Erosion Losses: A Guide to Conservation Planning*. USDA Agriculture Handbook #537, Washington.

Wischmeier, W.H. 1976. Use and misuse of the universal soil loss equation. *Journal of Soil and Water Conservation* 31(1), 5-9.

Wolfe, S.A., Huntley, D.J., David, P.P., Ollerhead, J., Sauchyn, D.J., & MacDonald, G.M.. Submitted. Geochronologic evidence for widespread dune activity induced by late 18th century dryness, Great Sand Hills, southwestern Saskatchewan. Canadian Journal of Earth Sciences.

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
- high inter-annual climatic variability
- mixed grass prairie
- extreme temperature seasonality

Hydrography
- major rivers are throughflowing
- mostly intermittent streams
- significant snow melt runoff
- large area of internal drainage

Geomorphology
- poorly integrated drainage network
- glaciated sedimentary basin
- underfit streams in glacial meltwater valleys
- 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 CAPTIONS

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.

FIGURE 1 ONLY AVAILABLE IN HARD COPY