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A Model of Fragmentation Resulting From Human Settlement in the Boreal Forest of Saskatchewan

by

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ABSTRACT

The most prevalent and persistent cause of forest fragmentation is agricultural settlement. The mechanized form of agriculture and the species of crops grown should determine where settlement occurs on the landscape. A spatially exact decision model that uses physical characteristics to determine the ease with which the landscape could be cultivated found that adjacency to neighbours, amount of stoniness, soil type, and soil texture govern the fragmentation process. To explain discrepancies between settlement simulations and empirical settlement data, a topographic index was used to capture the variability of soil properties according to hillslope position. Results showed that settlers were selecting higher hillslope positions but were not detecting differences between geomorphic substrates. Therefore, settlers seem to use observable attributes such as stoniness, nearness to neighbours, soil type, soil texture and hillslope position when making settlement decisions.

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INTRODUCTION

Fragmentation is the process by which natural ecosystems are converted into human determined ecosystems (Hunter 1996). Humans have modified large areas of the landscape throughout the world, the most prevalent and permanent type of human disturbance being agricultural settlement. Since the 16th century, Europeans have been spreading outward to other continents, advancing at an uneven pace from well established coastal settlements to the interior (Turner 1962, Grigg 1982, Cronon 1983, Whitney 1994). As a result of this long history of settlement, landscapes in temperate zones are among the most highly altered and fragmented, whereas within tropical zones fragmentation is a comparatively recent phenomenon.

The transformation of the landscape by land clearance, logging and agriculture is well recognized (Raup and Carleson 1941, Pyne 1982, Cronon 1983, Russell 1983, Foster 1992, Foster *et al.* 1992, Motzkin *et al.* 1996, Schneider 1996, and others) yet still poorly understood. Ecological studies have generally examined fragmentation in one of two ways. One approach has been to use time sequence maps and simple metrics or correlations to describe the spatial patterns produced by the fragmentation process (Curtis 1956, Krummel *et al.* 1987, O'Neill *et al.* 1988, Moss and Davis 1994, Simpson *et al.* 1994, Blackstock *et al.* 1995, Schumaker 1996). A second approach has been to assume that fragmentation can be simulated by statistical distributions, such as Poisson and negative binomial distributions (Olsson 1968, Hudson 1969, Franklin and Forman 1987, Gardner *et al.* 1987, Baker 1989, Turner *et al.* 1989a, Gardner and O'Neill 1991, Gustafson and Parker 1992), or by simple probability rules assumed to underlie the random process, such as in percolation theory (Gardner *et al.* 1989, Turner *et al.* 1989b, Knaapen *et al.* 1992, Boone and Hunter 1996, Metzger and Décamps 1997). Both of these approaches have limited predictive power because processes have been inferred from patterns in descriptive ways and not defined in forms testable for causality (Schumaker 1996). It is impossible to know which processes are responsible for generating the patterns when the patterns have not been linked to the physical, social and biotic mechanisms that interact to form the fragments.

Recognizing that agriculture is the most important fragmentation process in terms of absolute area of associated habitat loss (Hunter 1996), fragmentation can be defined as the spatial realization of landscape transformations produced by the rule-based settlement process. It follows that the settlement decision rules of the fragmentation process can be used to predict which parts of the landscape are more likely to experience human disturbance and which are more likely to be left as forested remnants. This approach is more desirable than either the simple metric approach or the neutral model approach because the patterns produced by the fragmentation model are understood in terms of the decision processes producing them.

The objective of this study was to model the decisions that lead to fragmentation. The first step was to determine if settlers were basing their decisions on the ease with which the landscape could be settled. The highly mechanized form of agriculture used in the study region suggests that the decision rules of the settlement process should reflect the way in which the landscape was cultivated. A spatially realistic transition model of fragmentation (settlement) was used to determine which combination of biophysical and socioeconomic landscape variables (*e.g.* stoniness, distance to transportation networks) were most important in characterizing areas of settlement and cultivation. Only variables shown to have been correlated to settlement and available to settlers at the time of settlement were considered (*e.g.* Bylund 1960, Ellis and Clayton 1970). The model was spatially realistic in that the socioeconomic and biophysical variables of a specific location were based on actual empirical values for a real landscape. The relative importance of each variable was determined by comparing the distribution of settlement on the landscape to the distribution of various socioeconomic and biophysical variables available to the settlers at the time of settlement.

The second step in modeling the fragmentation process was to use a topographic index to determine the productivity of the landscape. The topographic index was not used in the settlement model because it is unknown whether settlers had any understanding of surficial geology at the time of settlement. The topographic index uses the structure of the landscape to determine the amount of water that flows through any point by its position relative to other points (*i.e.* areas of lower elevation receive moisture from areas of higher elevation) and the rate at which the moisture passes through the point (*i.e.* the slope). Given that all landscapes can be characterized by spatially recursive partitions of the fluvial surface into hillslopes arranged around a topographic skeleton of stream links and ridge lines (Band 1989), this topographic index can be used to predict the distribution of water and surficial materials on any landscape.

The rates of change and location of water and surficial materials down the hillslope is determined by the shape of the hillslope (O'Loughlin 1981, Wood *et al.* 1988, Bridge and Johnson 2000) which in turn is defined by the surficial geology (Hack and Goodlet 1960, Bull 1975, Bridge and Johnson 2000). The specific moisture and nutrient requirements of crops suggests that the decision rules of the settlement process should also reflect the productivity of the landscape (Lloyd and Dicken 1972, Meinig 1979, Odum 1983, Hall *et al.* 1995). To determine if settlers were basing their decisions on the productivity of the landscape, the change in the distribution of water and surficial materials predicted by the topographic index was compared to the change in the distribution of settlement on the landscape over time.

Settlement Model

A spatially realistic transition model of land use change developed by Hall *et al.* (1995) was used to predict the nature of the sites that settlers chose in terms of socioeconomic and biophysical variables. The model is spatially realistic in that predictions are based on actual homestead units and socioeconomic and biophysical variables of a specific location are based on the empirical values of a real landscape. The settlement decision process was modeled using a settlement suitability index (S_i) that assumes settlers weight certain easily accessible socioeconomic and biophysical variables according to how well they reflect the ease of cultivation, productivity, and access to markets. As the governing equation of the settlement process, the settlement suitability index (S_i) represents the likelihood that a particular location (i) will be selected for settlement. The weighted average of the socioeconomic and biophysical variables (j) at location (i) was calculated by:

$$S_i = \sum^{n}_{j=1}(X_{ij} W^*_j) \tag{1}$$

where:

X_{ij} is the socioeconomic and biophysical variables used to determine productivity.

W^*_j is the relative importance (weight) of the socioeconomic and biophysical variables used by the settlers.

To make the variables (X_{ij}) comparable (*i.e.* variables were categorical), variable categories were compared to empirical records of past settlement and converted to a percent settled variable value by determining the proportion of categories **(k)** within each variable **(j)** that were more likely to be settled:

$$X_{ij} = N^*_{kj} / N_{kj} \tag{2}$$

where:

N^*_{kj} is the number of pixels of a particular category (k) that have been settled for each socioeconomic or biophysical variable (j).

N_{kj} is the total number of pixels of a particular category **(k)** for each socioeconomic or biophysical variable (j).

The relative importance of the socioeconomic and biophysical variables (W^*_j) was determined by:

$$W^*_j = W_j / \sum^{n}_{j=1} W_j \tag{3}$$

where:

W_j is the importance of (X_{ij}) on the first principal component which is defined as:

$$W_j = \mu_j(\lambda / S_{jj})^{1/2} \qquad (4)$$

where:

μ_j is the eigenvector of percent settled variable for the first principal component.

λ is the eigenvalue of the first principal component.

S_{jj} is the covariance matrix score for the percent settled variable (X_{ij}).

The settlement suitability index (equation 1) is the governing equation of the two step settlement process used to predict the pattern of fragmentation on the landscape. First, certain categories within a variable (X_{ij}) were more likely to be settled than other categories. Second, certain socioeconomic or biophysical variables were more important than other variables to settlement (W^*_j). The suitability index values (S_i) were ranked from largest to smallest on the landscape and the settlement process was simulated by searching the landscape for locations with the highest settlement suitability values (S_i). A location with a high settlement suitability value (S_i) meant that it had a high probability of being settled.

It should be stressed that the settlement model and the algorithm that implements the model were developed with the following assumptions. The first assumption is that the forest of the study area has been fragmented by agricultural settlement. Other activities, governed by different decision rules, may fragment the forest in other areas. The second assumption of the model is that future settlement occurs at locations with values similar to those of previously settled areas. This means the model is most effective when the amount of settled land is small and growing because the data can distinguish most clearly the geographic characteristics associated with cultivation. The third assumption of the model is that the ability to accurately extrapolate land use change depends on the association between the socioeconomic and biophysical variables and the pattern of land use change (settlement). Because a close association is not sufficient to conclude causation, there must be some insight into why these variables are important for agriculture. This assumption was met by using only biophysical and socioeconomic variables that have been shown to be important for agricultural settlement. The fourth assumption of the model is that the decisions used to select areas for cultivation do not change over time. To address this assumption, simulations were run over time periods of varying lengths and compared to empirical settlement data. The fifth assumption of the model is that cultivation intensity (*i.e.* the amount of fragmentation) is constant over time and that the rate of land use change is accurate. This assumption was met using a linear interpolation of the number of locations that change from forest to agriculture in the empirical settlement data during a particular time period. Finally, the model assumes that land use change is permanent and that variation of land use is not distinguishable within a cell. This means that one must exercise caution when using this model to predict changes over a very long time or over large areas. For this study, relatively short time periods (*i.e.* ten to sixty years) were used. Cell size is 90 m^2; this cell size captures the variability in biophysical and socioeconomic variables and is representative of the size of a homestead (*e.g.* homestead = 1 quarter section = 160 acres = 7200 cells).

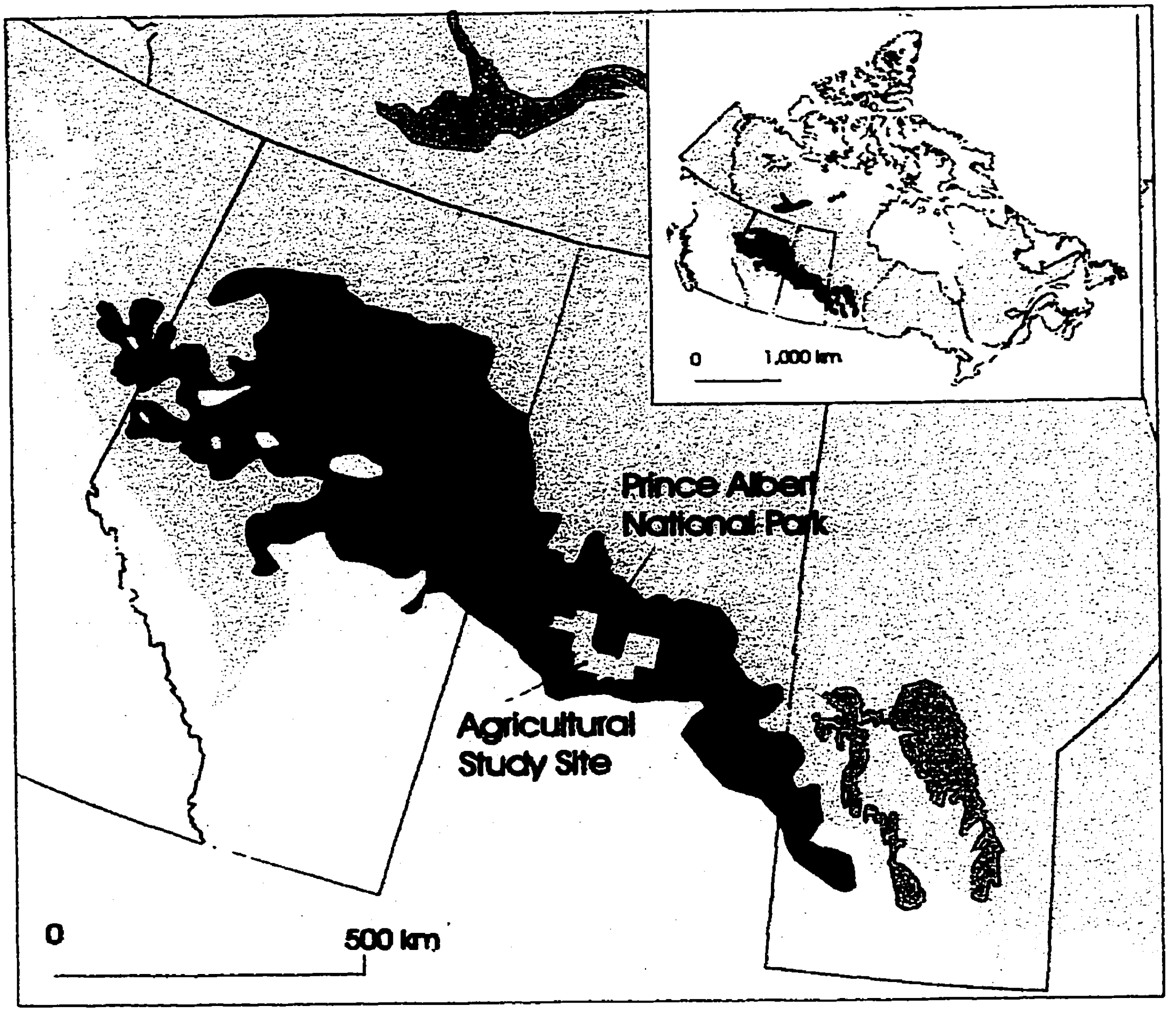
METHODS

Study Area

The study area is a 1930 km^2 agricultural region located just south of Prince Albert National Park in the southern edge of the boreal forest in central Saskatchewan, Canada (Figure 1, see also Weir and Johnson 1998, 2000 for maps of the area). It is representative of the southern edge of the boreal forest, characterized by a uniform continental climate with a short growing season (less than 100 frost free days), and an average summer temperature of 20 °C (Fitzgerald 1965, Padbury *et al.* 1978). Average annual precipitation ranges from 400 mm to 500 mm, with 70% occurring as rain. The topography ranges in elevation from 510 to 580 m a.s.l. Most of the area possesses either grey and brownish grey podsolic soils or transitional black-grey (degraded black and wooded calcareous) soils. Stones and boulders are present in areas of sandy outwash, fluvial, and till except where soils have developed on lacustrine deposits. The original forest cover of the study area has been modified and today is primarily composed of small isolated fragments of forest. It was originally covered by continuous mixedwood boreal forest (Weir and Johnson 1998). Remnant patches of forest in upland sites consist of aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), paper birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.) and balsam fir (*Abies balsamea* (L.) Mill.). On lowland sites the remnant stands of forest are composed of black spruce (*Picea mariana* (Mill.) BSP.) and tamarack (*Larix laricina* (Du Roi) K. Koch).

The study area was selected for two reasons. First, it is representative of the discontinuous

Figure 1. The study area (yellow) is located within the agricultural region of the southern edge of the mixedwood boreal forest, south of Prince Albert National Park in central Saskatchewan, Canada. The light blue area represents the extent of the boreal forest in Canada and the dark green area is the southern mixedwood boreal forest.

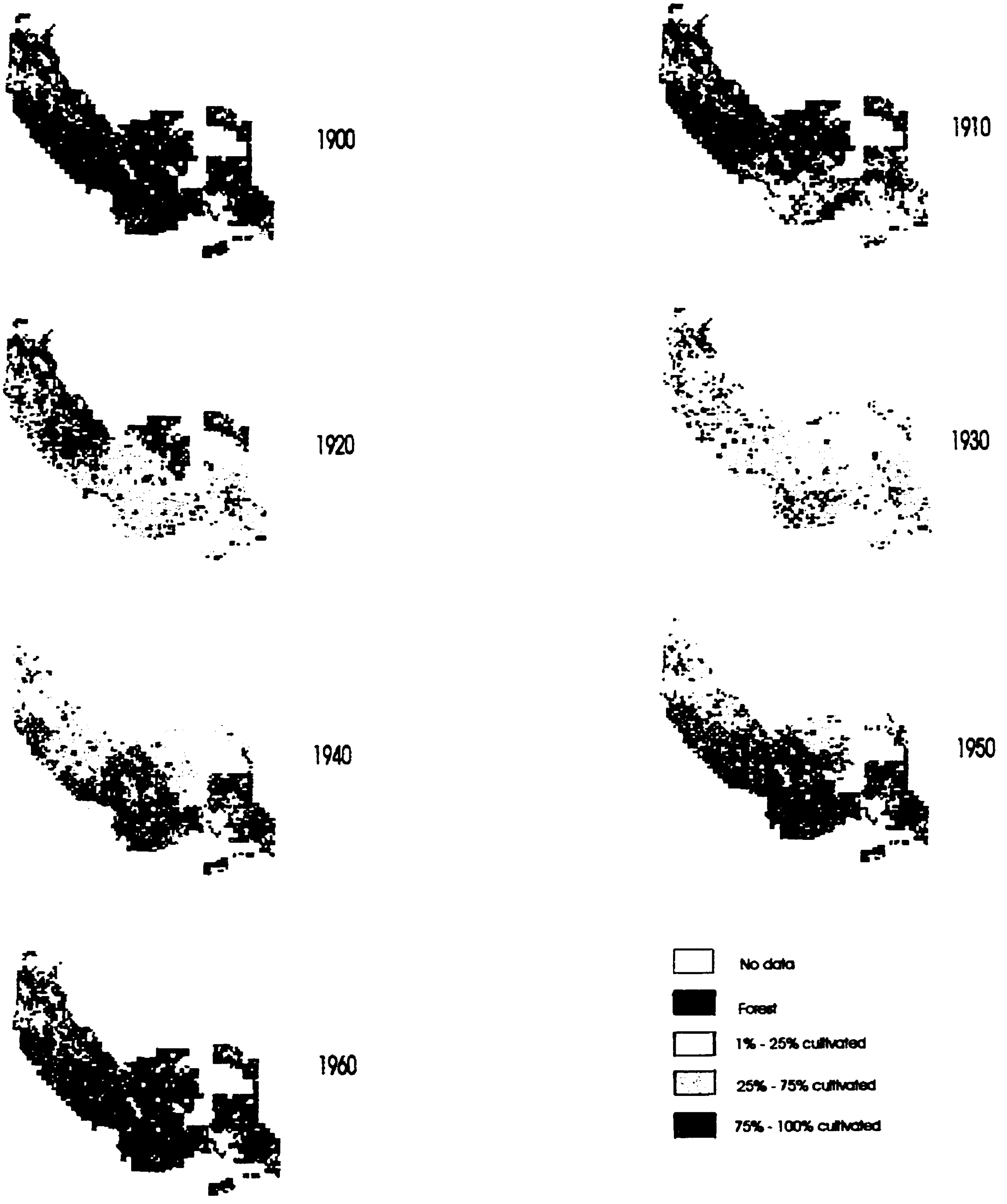

Prince Albert National Park
Agricultural Study Site
0
500 km
0
1,000 km

settlement front that characterizes the southern edge of the boreal forest. This front, considered to be one of the last frontier areas for settlement (Vanderhill 1958, 1982), stretches across Canada from northern British Columbia to central Ontario as well as parts of Sweden, Finland and Russia. Second, the long history of settlement throughout the study area meant that homestead records and empirical maps of past settlement activities could be used to determine which characteristics settled areas had in common.

Agriculture in central Saskatchewan consists primarily of grain (wheat and oats) and livestock operations (Stutt and Van Vliet 1945). According to the Homestead Act, a settler was expected to cultivate 15-30 acres of land for 3-4 consecutive years between the claimed date (*i.e.* the date when a settler claimed and began to reside on a 160 acre homestead) and the patent date (*i.e.* the date the land's patent was transferred to the settler) (Allen 1889, Fitzgerald 1965, Weir *et al.* 2000). Organized settlement of the study area began in 1890 after lands in the southern part of the province were largely occupied (Figure 2), with settlement density increasing from east to west and from south to north.

Human technology and large scale mechanization in agriculture since the 1900s have resulted in the continual clearance of economically marginal lands in the southern edge of the boreal forest (Fitzgerald 1965, Davies 1973, Vanderhill 1982). Three farm settlement phases can be differentiated in Figure 2: a colonization phase (1920-1930), where settled areas were uncommon and independent of each other; a spreading phase (1930-1940), where the density of settlements rapidly increased; and a competition phase (1940-1950), where the

Figure 2. The historical settlement pattern for the 2978 homesteads in the mixedwood boreal forest south of Prince Albert National Park as determined from homestead records and forest conversion rates.


1900
1910
1920
1930
1940
1950
1960
No data
Forest
1% - 25% cultivated
25% - 75% cultivated
75% - 100% cultivated

environmental limitations restricted settlement density and where competition for space became increasingly important (Fitzgerald 1965).

Data

The biophysical and socioeconomic variables used in this study include soil texture, soil type, hillslope steepness, amount of stoniness, distance to transportation networks (road and railroad), and nearest neighbour. Past studies have shown these variables to be correlated to settlement (Bowman 1931, Bylund 1960, Birch 1967, Mahaney and Ermuth 1974, Meinig 1979, Nualchawee *et al.* 1981, Sader and Joyce 1985, Ludeke *et al.* 1990, Simpson *et al.* 1994, Ihse 1995, and others). Climate variables were not used in this study because of their uniformity across the 80 km wide study area.

The original data for soil, slope, and stoniness was supplied for each municipality by the Semiarid Prairie Agricultural Research Centre, Agriculture and Agri-Food Canada Research Branch. Photo maps (1:20 000) were used in the field to record soil landscape observations and to digitize the soil lines. Slope, stoniness, and soils were recorded as categorical data. The information was then compiled at 1:100,000 scale in NAD27, UTM Zone 13, *.dlg format. The soil coverages, supplied for each municipality, were joined with dbase files into a single polygon coverage. Arc Info raster grids were then created from the polygon coverage and converted to ERDAS images, which could be imported into IDRISI.

Digital base map information of township and range lines, section lines, road, and railroad lines were supplied by the GIS Centre, Saskatchewan Geomatics (SaskGeomatics) Division, Saskatchewan Property Management Corporation. The information was taken from a 1:1 M general purpose data set (grid road map) in NAD27, Zone 13, *.dxf and *.dwg format. Roads and railroads were extracted and the vector data layers converted to Arc Info grids. The proximity variables were recorded as the Euclidean distance from the centroid of a sampled grid cell to the nearest road, trail, or railroad. These raster grids were created in Arc Info, converted to ERDAS and imported into IDRISI.

Empirical settlement maps were compiled using historical archives and homestead records to determine the nature and timing of settlement patterns for all decades from 1890 - 1963, since this was when the majority of the study area was settled (Weir *et al.* 2000). Homestead records, which identified when land was both homesteaded (*i.e.* the claim date) and sold (*i.e.* the patent date), were used to determine the rates of conversion from forest to agriculture. The rate of conversion in acres per year and the percent of agricultural land that comprised a homestead was calculated for each settlement period following the methods of Weir *et al.* (2000). These database files were linked via township and range to a structured Township Fabric Map of quarter section coverage in NAD83, Zone 13, *.shp format supplied by the GIS Center, SaskGeomatics Division, Saskatchewan Property Management Corporation. Maps of the agricultural region displaying the percentage of agricultural land comprising these homesteads for each settlement period were then created in Arc Info, converted to ERDAS, and imported into IDRISI.

All empirical settlement data and all socioeconomic and biophysical variables were represented as thematic (*i.e.* categorical) grid maps. All maps were standardized to a size of 895 cell rows × 973 cell columns. The study area consists of a total grid cell count of 23 8376 cells. Each grid cell represents 90 m^2. All maps were georeferenced to the National Topographic System (NTS) coordinate system (NTS quadrangles covering areas of 15' Lat. × 30' Long).

The Digital Elevation Model (DEM), which represents the spatial distribution of elevations above some arbitrary datum in the landscape, was created from a TIN model supplied by the GIS Center, Saskatchewan Geomatics (SaskGeomatics) Division, Saskatchewan Property Management Corporation. The TIN model was in ASCII format and the files were organized according to the NTS. The TIN model is a list of points with x, y and z coordinates where each point (x, y coordinate) is associated with an elevation (z) value. Point data were interpolated using GRASS 4.2.1 to produce a raster file of elevation. Tension and smoothing parameters were then applied to create a more realistic surface. Relatively low values for tension and smoothing parameters were used owing to the relatively flat terrain of the study area. Full depression depitting and calculation of flow pointers, accumulations and directions was then carried out using GRASS 4.2.1. The topographic index was calculated on the raster versions of the flow pointers and directions and then converted to ASCII format.

Analysis

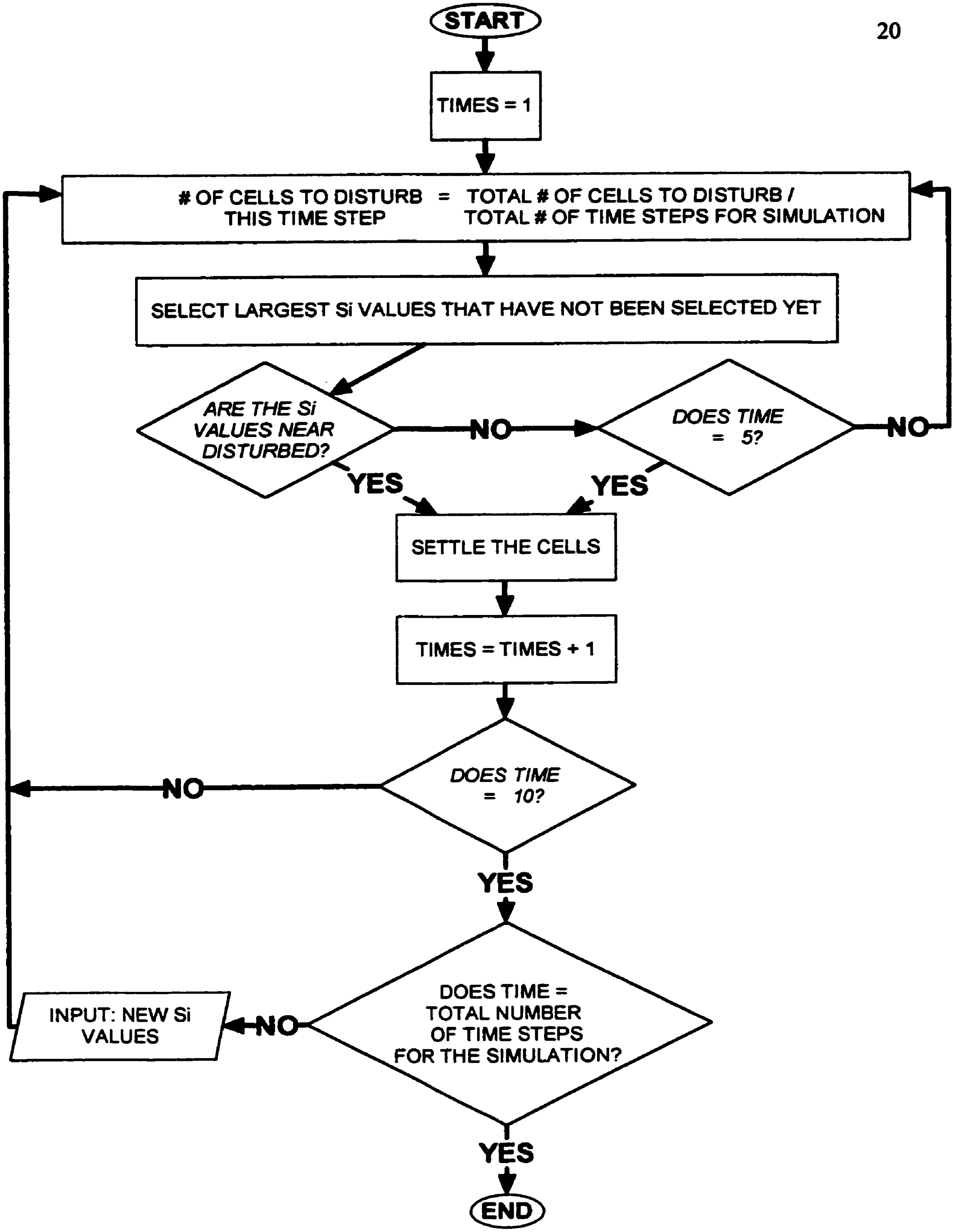
Settlement Model

To determine if settlers were basing their decisions on the ease with which the landscape could be settled, a spatially exact transition model of fragmentation (settlement) was used to determine which physical characteristics of the landscape (*i.e.* both socioeconomic and biophysical variables) were important in characterizing areas of settlement and cultivation. The model was validated both spatially and temporally. To validate the model spatially, the study area was divided in half (*i.e.* east and west). The western half was used to develop the decision rules, these rules were then used to simulate settlement on the eastern half. Once the model was validated spatially, fragmentation was then simulated temporally on the entire landscape. For this analysis, the decision rules were developed from an earlier time period (*e.g.* 1930) and then used to simulate settlement at a later time period (*e.g.* 1950).

Importance values for the categories within each variable were developed by comparing the variables to the empirical land use maps of the study area and calculating the proportion of categories that were most likely to be settled (equation 2). Only empirical maps that were greater than 20% but less than 85% disturbed were used to develop the importance values (X_{ij}) because a minimum number of cells must be disturbed for the settlement model to correctly select by PCA which variables were driving the settlement process (see first assumption of the settlement model). A Principal Components Analysis (PCA) of the percent settled variable values (X_{ij}) was run for each decade from 1900 to 1963 to determine which variables were most important in governing the fragmentation process. Each variable was then assigned a weight of relative importance (W^*_j) proportional to the variable's coefficient in the first principal component (equation 4), reflecting the correlation between the variable and settlement. Variables highly correlated to settlement received large weights and were more important in influencing land use change while variables less correlated to settlement received smaller weights. These relative weights (W^*_j), along with the importance values (X_{ij}), were used to develop the settlement suitability index (equation 1). Therefore, the settlement suitability index (S_i) was a weighted sum of all percent settled variables, computed for each location.

The settlement model was run for every decade in yearly time steps. Land use was simulated by incorporating into the model the settlement suitability index, the number of cells to be disturbed, and algorithms of adjacency and dispersion (Figure 3). For each time step in the simulation, the model used historical homestead records to determine how many cells to settle. This number was adjusted for each time step by subtracting the number of cells settled in the previous time step. The settlement model then located cells with the highest settlement suitability values and determined whether the locations with the highest suitability values were adjacent to previously settled cells. If the cells with high suitability values were adjacent to previously settled land, then the cells were settled (to mimic the tendency to develop near land that is already developed) and the model progressed to the next time step. If the cells were not adjacent to previously settled land, then the model located cells with the next highest settlement suitability index values and determined if they were near previously settled land. This continued until cells near previously disturbed cells were found. Once these cells were

Figure 3. The flow chart of the settlement model showing the incorporation of an adjacency algorithm.


START
TIMES = 1
# OF CELLS TO DISTURB THIS TIME STEP = TOTAL # OF CELLS TO DISTURB / TOTAL # OF TIME STEPS FOR SIMULATION
SELECT LARGEST Si VALUES THAT HAVE NOT BEEN SELECTED YET
ARE THE Si VALUES NEAR DISTURBED?
NO
DOES TIME = 5?
NO
YES
YES
SETTLE THE CELLS
TIMES = TIMES + 1
DOES TIME = 10?
NO
YES
DOES TIME = TOTAL NUMBER OF TIME STEPS FOR THE SIMULATION?
NO
INPUT: NEW Si VALUES
YES
END

settled, the model progressed to the next time step. At every fifth time step (*i.e.* every five years), the cells with the highest suitability values were settled to mimic actual patterns of frontier settlement, skipping over unfavorable locations for more favorable areas. This ensured that new areas of settlement were created in the frontier. The model then progressed to the next time step. Every 10 time steps (*i.e.* every ten years), the model either stopped, or the relative weights ($\mathbf{W}^*_j$) were changed and the simulation began again.

To verify the settlement model and confirm that the Principal Components Analysis correctly identified the variables driving the settlement process, the weights of the west side were used to simulate settlement in the east. Since the east side had not been used to develop the weights, simulations could be compared to empirical maps for verification. Success occurred when a grid cell in the simulated map matched the corresponding grid cell in the empirical map of land use. The percent of total cells that were correctly classified was calculated. Because it was assumed that disturbed cells could never return to an undisturbed state, a certain percentage of the grid cells were always guaranteed to be correct. These cells were removed from both the final simulated and the final empirical map before comparisons were made.

Having validated the model, settlement was then simulated across the entire landscape. For these simulations, empirical land use maps of an earlier date were used to develop the decision rules for the entire landscape, while empirical land use maps of a later date were used to verify the simulations. The percent of total cells classified correctly was again used to calculate overall success.

Statistical measures were not used to compare the simulated and empirical maps for two reasons. First, there currently is no agreed upon measure to determine whether two maps are statistically different (Li *et al.* 1993). Many test statistics cannot tell if a misclassified cell is far from or near to the correct location and therefore two different simulated maps can have the same statistic. Second, the spatial pattern of mosaic maps are completely different from point dot maps and therefore the matching of maps is not a straightforward statistical procedure. Most statistical tests ignore differences in spatial patterns between two maps and instead concentrate on deviations from standard, random distributions.

Topographical Index

To determine if settlers were basing their decisions on the productivity of the landscape, the second step in modeling the fragmentation process was to use a topographic index to predict the distribution of water and surficial materials on the landscape. The definite structure of the landscape implies that similarity in patterns of terrain attributes exist between landscapes. According to the catena concept, soils from different catenary positions are connected by the continuous flow of water and materials carried in the water; they differ because of variation in relief and in drainage.

The topographic index, developed by Beven and Kirkby (1979), is a quantitative method of showing hillslope position by incorporating specific catchment area and surface slope angle to represent underlying physical processes (Beven and Kirkby 1979). It accounts for the variation in relief and drainage by determining the surficial flow of water, solutes and sediments to a particular point on the hillslope within a watershed. Assuming that surface water flow is an adequate indicator of the distribution of water and surficial materials and that these surficial processes are more readily observable by the settlers than groundwater discharge and recharge, the hillslope is chosen as the basic functional unit of the landscape because it has well defined hydrologic and geomorphic boundary conditions (Abrahams 1984, Band 1986, 1989). The spatial distribution of the index can be readily calculated from a digital elevation model (DEM) to predict conditions of relative wetness and variations in hydrological and ecological processes within watersheds:

$$\mathbf{W}_i = \mathbf{\mathit{l}n}\ (\mathbf{A}_s / \tan\beta) \qquad (5)$$

where:

ln is the natural logarithm.

A_s is the specific catchment area per unit contour length (*i.e.* the up slope contributing area per unit width of contour).

tanβ is the tangent function of the local surface slope angle (°).

The specific catchment area per unit contour length (A_s) measures the surface and shallow subsurface runoff at any given point on the landscape:

$$\mathbf{A}_s = (\mathbf{A}_v * \mathbf{C}_a) / \mathbf{C}_s \qquad (6)$$

where:

A_v is the depitted accumulation value (*i.e.* total number of cells that drain through a cell).

C_a is the area of cells in the raster layer (m^2).

C_s is the linear size of cells in the raster layer (m).

To run the topographic index on the landscape, drainage networks (*i.e.* hillslopes, streams and ridges) must be derived using flow algorithms and a digital elevation model (DEM). The structure of a contour-based DEM can be used to determine the flow of water and nutrients on the landscape since it represents the spatial distribution of elevations above some arbitrary datum. To ensure that the water flow reached a logical destination (*i.e.* lake or stream), the DEM was first depitted (a pit is a single cell surrounded by cells of higher elevation). A flow algorithm was then used to define the ridge lines, stream networks and hillslope catchments by calculating the number of cells draining into a given cell (*i.e.* the drainage accumulation). In this study, ridges were defined as cells having no contributing cells. To delineate the stream network, a drainage threshold was applied to each pixel such that accumulations above the threshold marked the pixel as a stream (*i.e.* a high threshold includes the main stream and tributaries with the greatest drainage area, while a low threshold includes larger numbers of increasingly smaller tributaries). Thresholds were chosen so that streams began at locations that best matched positions of stream heads located on aerial photographs, producing the most realistic stream network. Based on these definitions of ridge lines and stream courses, a hillslope catchment was defined as the area extending from a central seed pixel up slope to a point of minimum drainage accumulation (*i.e.* the ridge line) and downslope to a point of maximum drainage accumulation (*i.e.* the stream).

Once drainage basins and stream networks were delineated, the topographic index was run on the newly defined landscape to predict the distribution of soil properties and water movement in the catchment (equation 5). To determine if settlers were basing their decisions on the productivity of the landscape, a chi-square goodness of fit test compared the distribution of topographic index values available to the settlers at the time of settlement to the distribution of topographic index values selected by the settler.

RESULTS

Settlement Model

Variable loadings from the first principal component, which accounted for 40% - 61% of the variation in percent settled on the western half of the study area (Table 1), were used to determine the settlement suitability index maps for the eastern half of the study area. Large positive loadings were found for stoniness, soil type, and soil texture (Table 1) . The second principal component was not used in the analyses since it only accounted for an additional 13% - 31% of the variation (Table 2).

When maps of model simulations for the east side were compared to empirical settlement maps, the percent of total cells classified correctly ranged from 45% - 68%, depending on which map was used to develop the decision rules. This shows that the model was valid in

Table 1. The proportion of the variation explained by the first principal component and the adjusted loadings of the variables calculated from an initial empirical settlement map of the west side (where the definition of settled varies according to what proportion of the cell is deforested). All loadings were adjusted to relative importance values (weights) to reflect the correlation between each variable and the principal component (equation 4). The largest weights for each simulation are in bold.

Year of settlement map	% deforested defined as settled	(Percent of variance) PC 1	Adjusted loading (weight) of Soil Form (W_j)	Adjusted loading (weight) of Rail (W_j)	Adjusted loading (weight) of Road (W_j)	Adjusted loading (weight) of Slope (W_j)	Adjusted loading (weight) of Stone (W_j)	Adjusted loading (weight) of Texture (W_j)
1910	> 0%	60.8	**84.9**	21.8	10.3	11.8	**91.1**	**62.4**
1920	> 0%	51.0	**89.1**	8.8	12.6	8.3	**88.8**	**57.1**
1920	> 25%	60.0	**88.4**	17.6	12.5	8.8	**89.5**	**58.6**
1930	> 25%	47.8	**88.8**	17.4	13.8	11.9	**88.4**	**54.6**
1940	> 25%	47.4	**40.0**	16.3	11.7	**98.5**	1.3	13.9
1930	> 50%	56.5	**88.7**	15.3	12.7	8.0	**89.1**	**57.5**
1940	> 50%	40.1	**86.7**	14.1	17.3	36.4	**81.3**	42.4
1940	> 75%	54.3	**88.2**	12.0	12.7	8.9	**90.3**	**56.3**
1950	> 75%	39.4	**82.6**	10.7	18.2	**57.3**	**68.7**	33.0
1950	100%	51.9	**88.2**	14.0	12.7	8.4	**90.3**	**56.8**
1960	100%	43.9	**42.6**	11.2	13.4	**96.5**	15.4	14.8

Table 2. The proportion of the variation explained by the second principal component and the adjusted loadings of the variables calculated from an initial empirical settlement map of the west side (where the definition of settled varies according to what proportion of the cell is deforested). All loadings were adjusted to relative importance values (weights) to reflect the correlation between each variable and the principal component (equation 4). The largest weights for each simulation are in bold.

Year of settlement map	% deforested defined as settled	(Percent of variance) PC 2	Adjusted loading (weight) of Soil Form (W_j)	Adjusted loading (weight) of Rail (W_j)	Adjusted loading (weight) of Road (W_j)	Adjusted loading (weight) of Slope (W_j)	Adjusted loading (weight) of Stone (W_j)	Adjusted loading (weight) of Texture (W_j)
1910	> 0%	14.9	**50.5**	3.3	2.9	13.7	**40.6**	16.8
1920	> 0%	16.0	**78.3**	14.1	13.1	25.2	**81.4**	1.7
1920	> 25%	14.3	**44.9**	2.6	0.1	20.6	**44.2**	13.1
1930	> 25%	18.8	13.8	14.3	11.3	**95.4**	22.5	5.2
1940	> 25%	24.6	**83.1**	24.7	16.7	15.3	**73.9**	3.3
1930	> 50%	13.8	**44.3**	10.5	0.7	28.4	**44.2**	9.1
1940	> 50%	28.8	10.8	1.6	5.8	**92.5**	36.7	8.9
1940	> 75%	13.2	33.8	**73.5**	7.3	10	27.4	6.6
1950	> 75%	30.7	32.4	4.4	0.2	**81.4**	**52.8**	14.8
1950	100%	15.7	22.3	**43.0**	11.2	**82.5**	27.2	1.6
1960	100%	30.3	6.2	**98.0**	11.1	20.5	2.5	1.6

using the adjacency algorithm and in selecting stoniness, soil type, and soil texture to drive the settlement process. Figure 4 shows one of the model simulation maps of the east side, the corresponding empirical map of the same year (Figure 5), and a map of the differences between the model simulation and the corresponding empirical map (Figure 6). In the difference map, cells misclassified as settled by the model occurred throughout the study area while those misclassified as unsettled occurred in the north.

For the entire study area, the first principal component accounted for 46% - 59% of the variation in percent settled when an empirical settlement map of an earlier time period was used to determine which variables were responsible for settlement at some later date (Table 3). Given that the second principal component only accounted for an additional 17% - 29% of the variation (Table 4), only importance values from the first principal component were used to develop the settlement suitability maps for the entire study area over varying lengths of time. Figure 7 is an example of one of these settlement suitability index maps. All settlement suitability maps followed the same general pattern, with values declining from south to northwest.

The gradient of suitability values (Figure 8) across the landscape reflects the large positive loadings for stoniness, soil type, and soil texture (Table 5). In general, high suitability values (*i.e.* suitability values from 29 to 35) occur on fluvial or lacustrine deposits of sandy loam texture and on gentle slopes (*i.e.* 2 - 5%) free of stones (Table 5). Low suitability values (*i.e.* suitability values from 10 to 17) occur on glacial till deposits of clay loam on gentle to

Figure 4. An example of a simulated land use map for 1950 developed by the settlement model for the eastern half of the study area using weights from the western half of the study area.

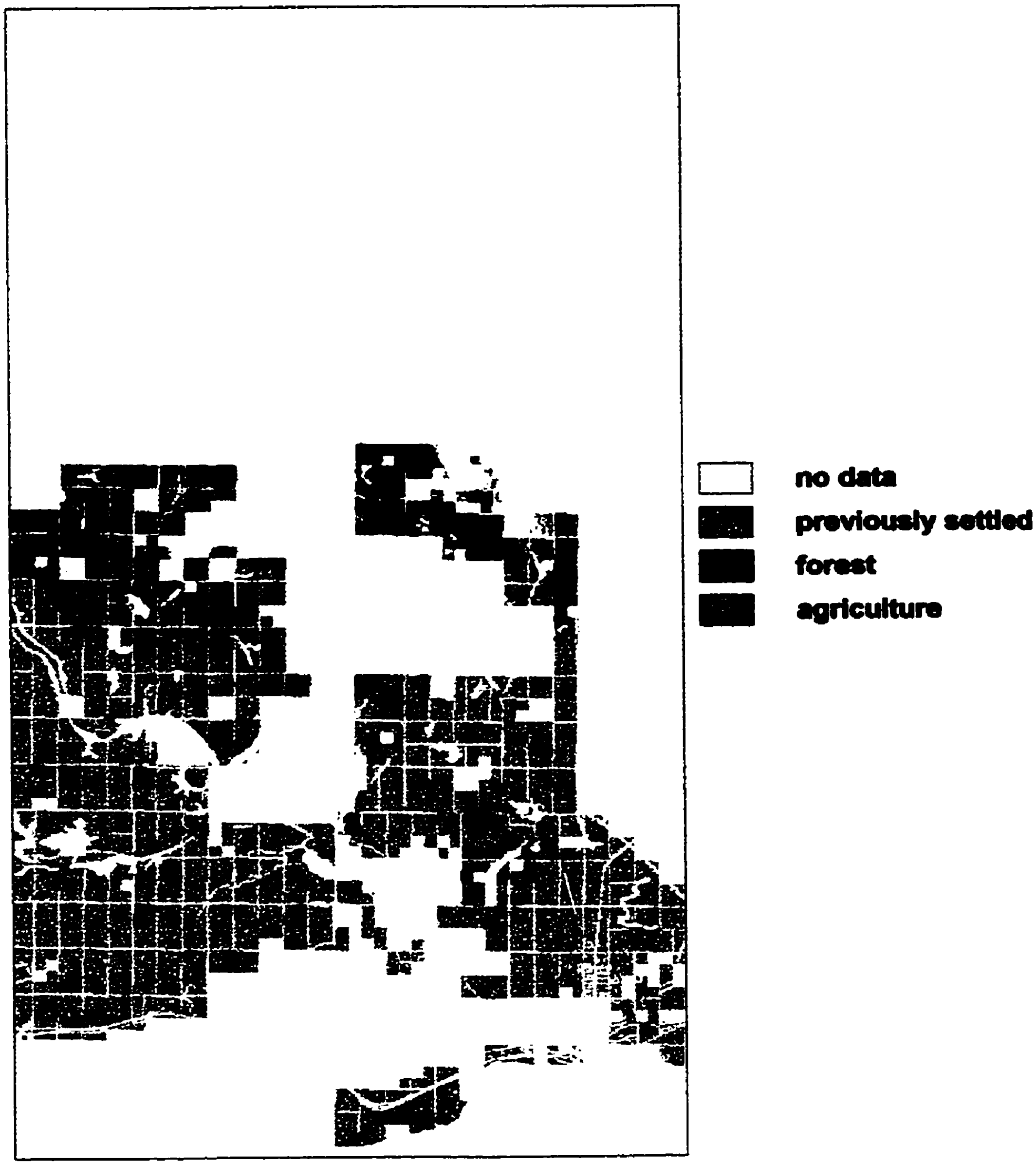

no data
previously settled
forest
agriculture

Figure 5. An example of an empirical land use map for 1950 for the eastern half of the study area.

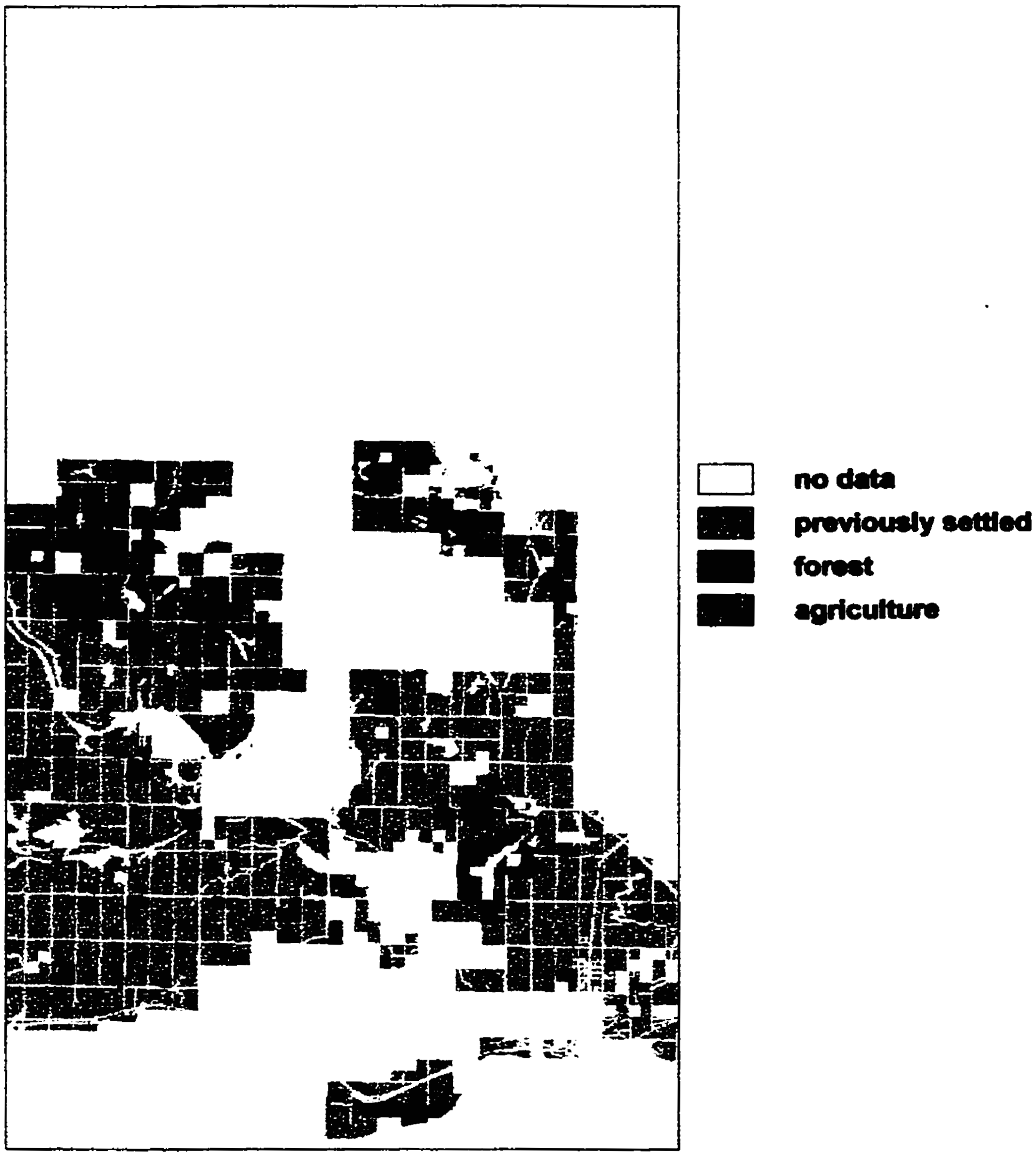

no data
previously settled
forest
agriculture

Figure 6. An example of the difference map showing the locations of the misclassified cells between the 1950 simulated (Figure 4) and 1950 empirical (Figure 5) land use change maps of the eastern half of the study area. Red represents areas misclassified by the settlement model as settled and blue represents areas misclassified by the settlement model as unsettled.

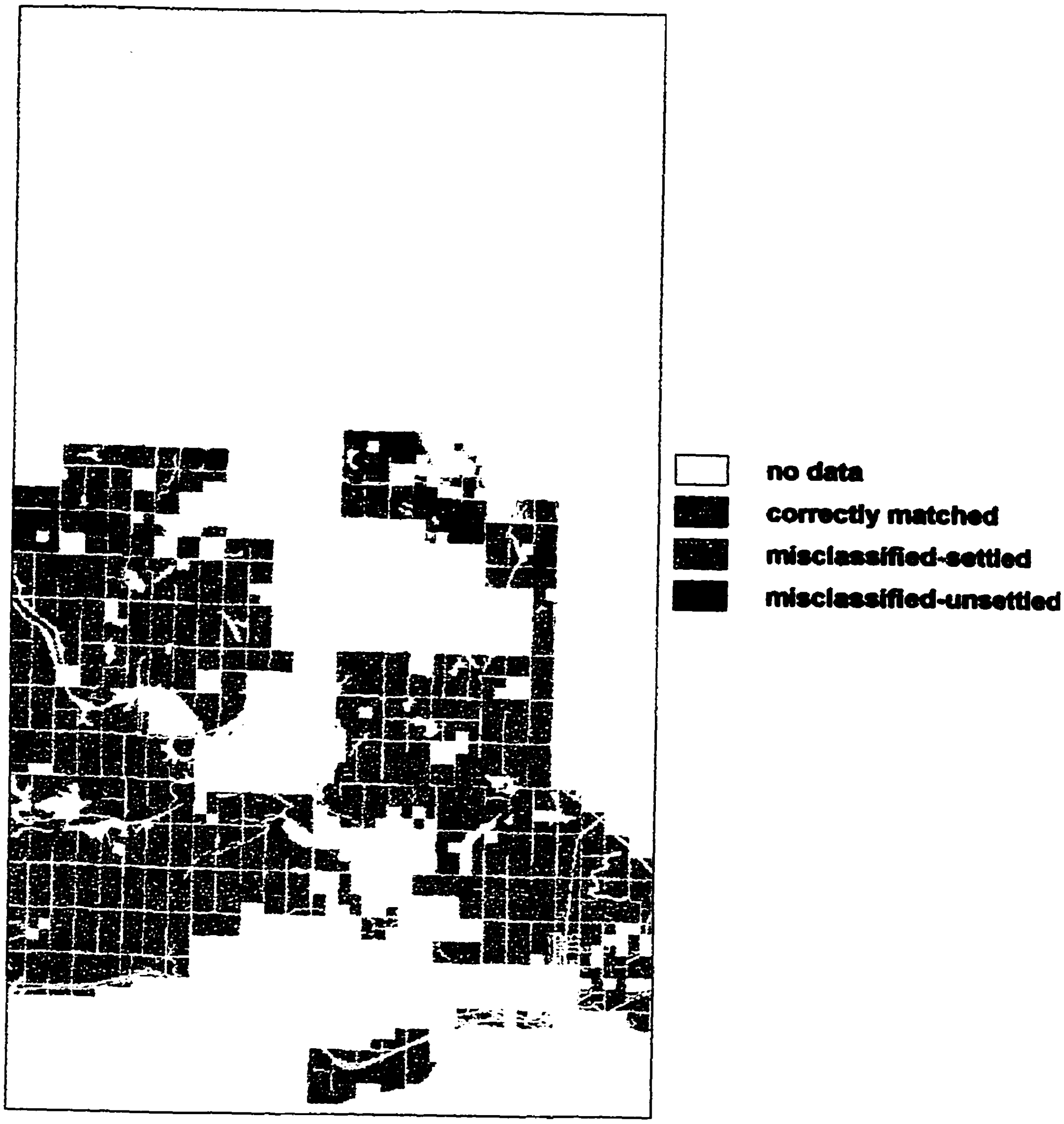

no data
correctly matched
misclassified-settled
misclassified-unsettled

Table 3. The proportion of the variation explained by the first principal component and the adjusted loadings of the variables calculated from an initial empirical settlement map of the entire study area (where the definition of settled varies according to what proportion of the cell is deforested). All loadings were adjusted to relative importance values (weights) to reflect the correlation between each variable and the principal component (equation 4). The largest weights for each simulation are in bold.

Year of settlement map	% deforested defined as settled	(Percent of variance) PC 1	Adjusted loading (weight) of Soil Form (W_j)	Adjusted loading (weight) of Rail (W_j)	Adjusted loading (weight) of Road (W_j)	Adjusted loading (weight) of Slope (W_j)	Adjusted loading (weight) of Stone (W_j)	Adjusted loading (weight) of Texture (W_j)
1910	> 0%	59.3	**87.2**	29.7	12.3	22.0	**93.9**	**68.4**
1920	> 0%	56.1	**89.6**	22.3	13.8	18.7	**93.3**	**65.8**
1920	> 25%	57.7	**89.2**	27.4	13.6	22.5	**93.9**	**66.0**
1930	> 25%	51.1	**88.3**	28.6	14.3	19.6	**93.0**	**64.2**
1940	> 25%	46.2	**71.2**	9.1	16.5	**87.4**	37.2	29.8
1930	> 50%	57.2	**89.4**	24.7	13.8	21.8	**93.8**	**65.4**
1940	> 50%	46.9	**86.8**	29.3	15.4	23.8	**92.6**	**59.4**
1940	> 75%	56.8	**89.4**	22.5	13.9	20.9	**93.7**	**64.5**
1950	> 75%	45.6	**87.9**	24.4	16.2	27.6	**91.6**	**57.1**
1950	100%	55.6	**89.4**	23.4	13.9	20.2	**93.4**	**65.2**
1960	100%	47.1	**88.9**	8.3	18.1	**50.4**	**78.7**	**50.2**

Table 4. The proportion of the variation explained by the second principal component and the adjusted loadings of the variables calculated from an initial empirical settlement map of the entire study area (where the definition of settled varies according to what proportion of the cell is deforested). All loadings were adjusted to relative importance values (weights) to reflect the correlation between each variable and the principal component (equation 4). The largest weights for each simulation are in bold.

Year of settlement map	% deforested defined as settled	(Percent of variance) PC 2	Adjusted loading (weight) of Soil Form (W_j)	Adjusted loading (weight) of Rail (W_j)	Adjusted loading (weight) of Road (W_j)	Adjusted loading (weight) of Slope (W_j)	Adjusted loading (weight) of Stone (W_j)	Adjusted loading (weight) of Texture (W_j)
1910	> 0%	17.1	22.2	**94.0**	1.4	0.8	2.7	11.8
1920	> 0%	16.7	21.3	**95.6**	2.1	8.3	7.1	8.8
1920	> 25%	18.2	20.9	**95.4**	1.9	0.6	1.0	5.6
1930	> 25%	21.9	23.8	**95.2**	0.4	11.5	1.4	8.4
1940	> 25%	28.6	58.8	12.5	10.6	**47.6**	**75.4**	31.5
1930	> 50%	18.3	21.2	**95.8**	1.9	2.5	3.2	6.0
1940	> 50%	22.1	25.7	**93.8**	1.2	24.9	0.4	6.6
1940	> 75%	17.9	21.2	**96.2**	2.2	4.1	4.7	5.9
1950	> 75%	20.6	22.4	**89.4**	1.7	42.3	8.5	1.2
1950	100%	19.0	21.4	**96.2**	2.2	5.2	3.8	7.0
1960	100%	28.8	16.5	6.3	1.4	**85.6**	**44.7**	12.5

Figure 7. An example of the settlement suitability index map for 1950 created by the settlement model for the entire study area using weights developed from an earlier time period (1930).

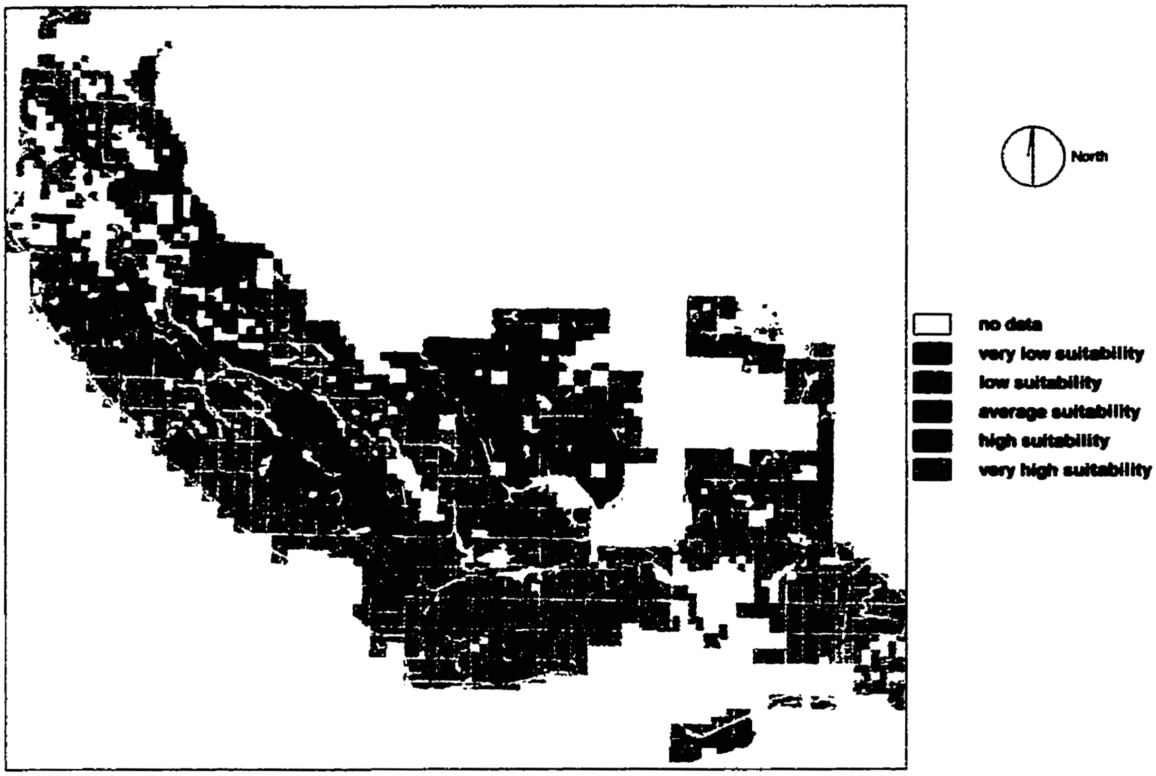

North
no data
very low suitability
low suitability
average suitability
high suitability
very high suitability

Figure 8. The distribution of suitability values (from Figure 7) for the entire study area before settlement (pre-1900).

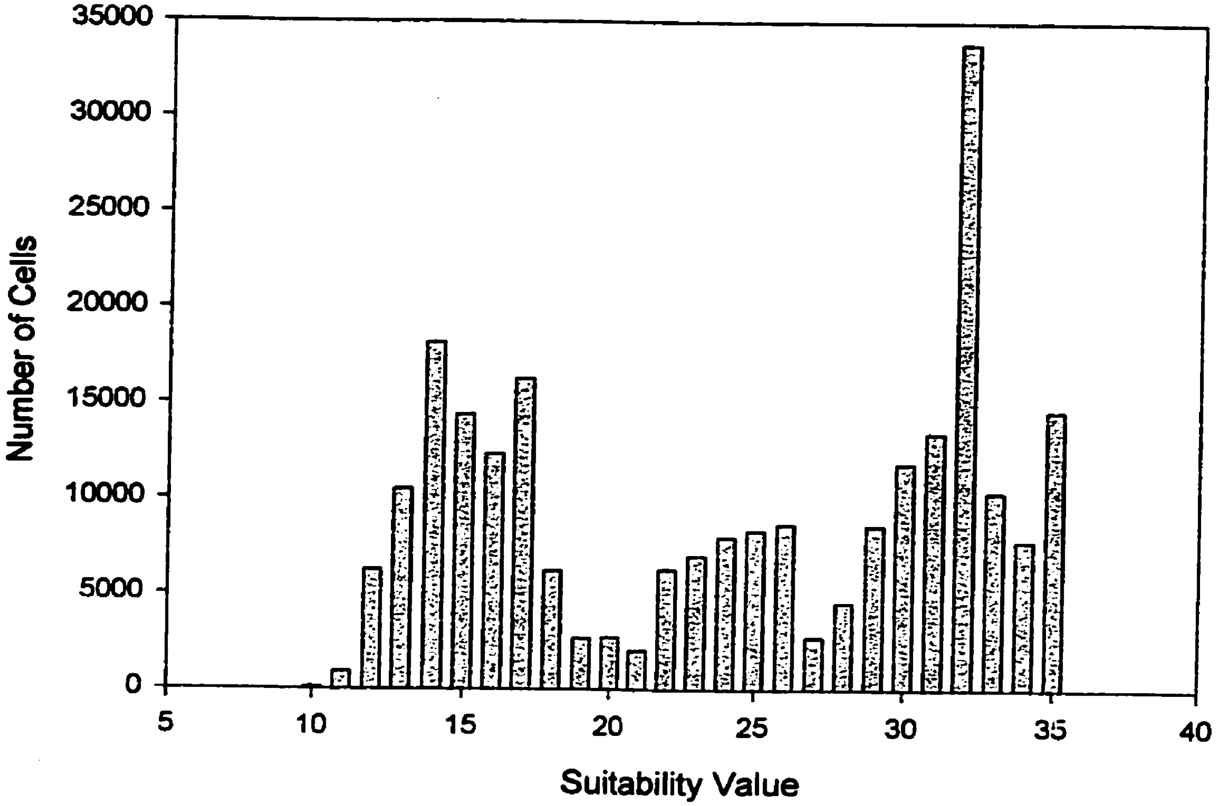

35000
30000
25000
20000
15000
10000
5000
0
Number of Cells
5
10
15
20
25
30
35
40
Suitability Value

Table 5. The proportion of categories within each variable described by a particular suitability value. The largest proportions are in bold.

Formation Attribute	Percent in low suitability	Percent in medium suitability	Percent in high suitability	Percent in suitability 14	Percent in suitability 32	Percent in suitability 21	Percent in suitability 27
alluvial	0.5	**17**	7	0.09	1	18	**41**
fluvial	0	8	**37**	0	**18**	9	36
lacustrine	0	**57**	**56**	0	**80**	**58**	23
till	**99**	13	0	**99.9**	0	0	0
depression	0	5	0	0	0	15	0
escarpment	0.5	0	0	0	1	0	0
TOTAL	100	100	100	100	100	100	100
Rail Attribute							
near (1 km)	12	16	23	8	5	11	46
2 km	13	15	21	17	27	6	31
3 km	14	12	20	23	31	0	2
4 km	16	12	18	28	28	7	3
5 km	27	14	11	20	9	1	2
far (6 km)	18	31	7	4	0	**75**	16
TOTAL	100	100	100	100	100	100	100
Road Attribute							
near (1 km)	18	19	24	16	23	10	22
2 km	17	18	21	15	23	11	15
3 km	17	18	19	14	21	15	16
4 km	17	17	17	14	17	16	15
5 km	14	13	11	20	11	**27**	12
far (6 km)	17	15	8	21	5	**21**	20
TOTAL	100	100	100	100	100	100	100

Slope Attribute	Percent in low suitability	Percent in medium suitability	Percent in high suitability	Percent in suitability 14	Percent in suitability 32	Percent in suitability 21	Percent in suitability 27
0 - 2 %	14	**29**	11	1	1	32	**25**
2 - 5 %	**53**	**49**	**77**	**63**	**91**	16	**72**
5 - 10 %	**28**	20	10	33	8	**48**	3
10 - 15 %	3	2	2	1	0	4	0
15 - 30 %	2	0	0	2	0	0	0
TOTAL	100	100	100	100	100	100	100
Stones Attribute							
none	0	23	**99**	0	**100**	15	**51**
slight	28	**60**	1	0	0	36	**46**
moderate	**71**	17	0	**99**	0	**49**	3
very	1	0	0	1	0	0	0
excessive	0	0	0	0	0	0	0
TOTAL	100	100	100	100	100	100	100
Texture Attribute							
fine gravel / sand	0	2	26	0	1	0	3
sandy loam	15	**34**	**52**	6	**90**	13	**52**
clay loam	**85**	**46**	12	**94**	0	**43**	**44**
clay / silty clay	0	13	10	0	9	29	1
organic	0	5	0	0	0	15	0
TOTAL	100	100	100	100	100	100	100

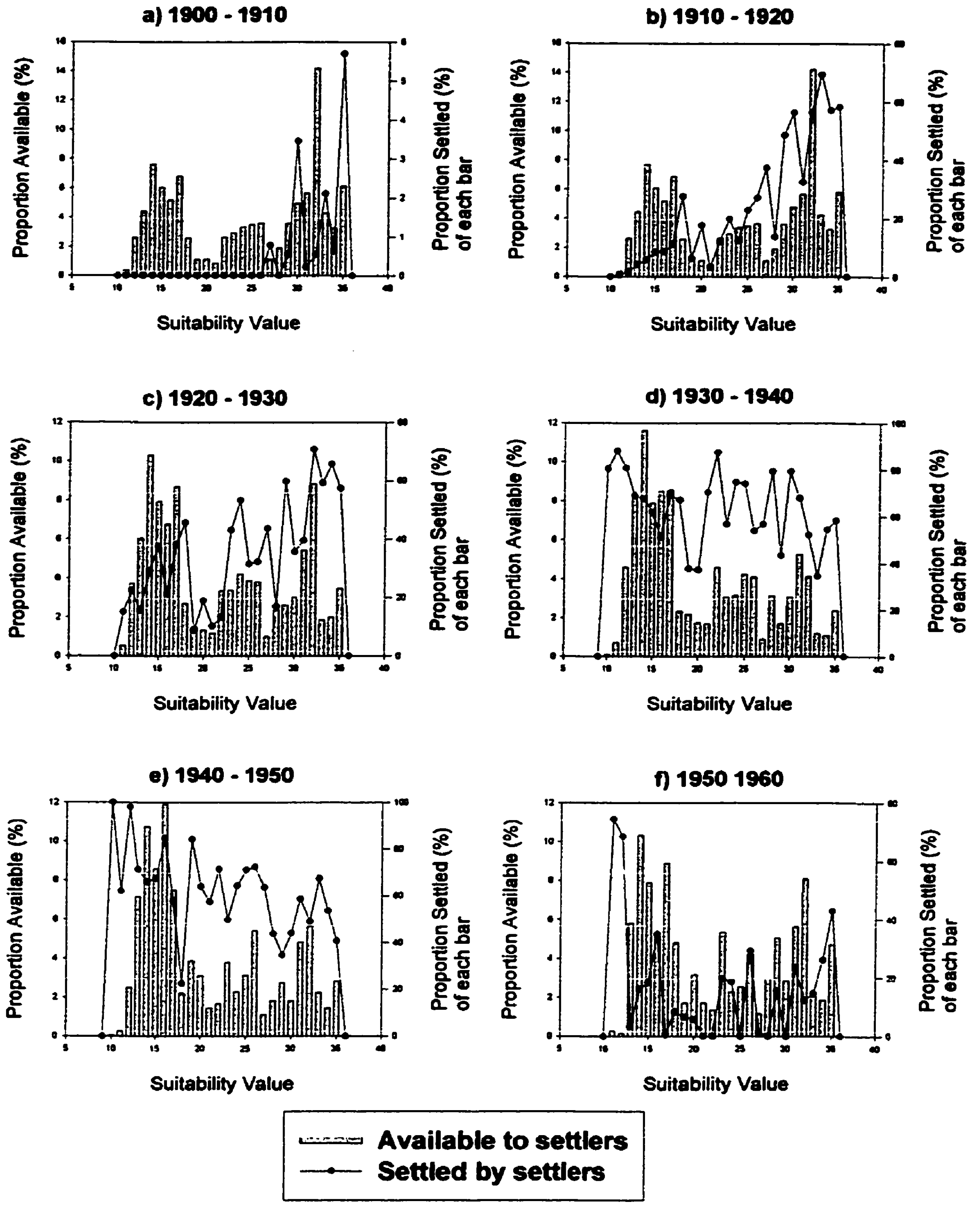
moderate slopes (*i.e.* 2 - 10%) with moderate stoniness (Table 5). Therefore, the gradient of suitability values across the landscape is a gradient of available moisture and nutrients and ease of cultivation.

The distribution of suitability values across the landscape consists of three peaks (Figure 8). One peak occurs at a relatively low suitability value (Figure 8 ~ value 14). Areas classified with a suitability value of 14 occur primarily in the west and northwest on undulating to rolling moraine (glacial till) sites (Figure 7). Over 99 % of the area classified with a suitability value of 14 is characterized by clay loam soils and moderate stoniness (Table 5). On the landscape, these values occur in areas where wooded vegetation had a strong impact on soil formation. A second peak occurs at a relatively high suitability value (Figure 8 ~ value 32). Areas classified with a suitability value of 32 occur primarily in the south and southeast on level to undulating plains of glaciolacustrine and glaciofluvial origin (Figure 7). These areas are characterized by sandy loam soils with gentle slopes (*i.e.* 2 - 5%) and no stones (Table 5). All areas classified with a suitability value of 32 occur in forested areas on undulating or hummocky landscapes. Between these two extremes is a smaller peak in abundance for the suitability value of 26. This value occurs throughout the area, bordering the moraine and outwash landscape formations (Figure 7). Areas classified with a suitability value of 26 are defined by a mixture of high and low suitability characteristics, occurring on old glacial lakes with alluvial and lacustrine deposits of sandy or clay loam and on level to gentle slopes (*i.e.* 2 - 10%) with slight to moderate stoniness.

There are also two suitability values that are not very abundant on the landscape (Figure 8, values 21 and 27). Areas classified with a suitability of 21 are scattered throughout the middle of the landscape (Figure 7) and tend to occur on lacustrine deposits of clay loam texture, moderate slope (*i.e.* 5 - 10%) and moderate stoniness (Table 5). These areas also tend to occur farther away from roads and railroads (Table 5). Given the flat topography of the landscape, roads and railroads tend to be ubiquitous throughout the area. Therefore, areas far from roads and railroads occur infrequently on the landscape. Areas classified with a suitability value of 27 are also uncommon and are scattered throughout the southwest part of the study area (Figure 7). These areas tend to occur on sandy or clay loam soils formed on alluvial deposits on level to gentle slopes (*i.e.* 0 - 5%) with few stones (Table 5). Given that alluvial soils range widely with respect to agricultural capability, and that they are often associated with narrow bands on valley bottoms, areas classified with a suitability value of 27 are small and irregular.

Recognizing that suitability values correspond to features on the terrain, the decision process can be described by comparing the proportion of a particular suitability value that is settled in any given time period relative to the occurrence of that suitability value on the landscape. From 1900 to 1910, settlement occurred exclusively in the south (Figure 2). Given that the entire southern area is characterized by high suitability values (Figure 7) it is understandable that suitability values ranging from 27 to 35 were the only values settled at this time (Figure 9a). As settlement spread northwest from 1910 to 1920 (Figure 2), many of these highly suitable areas were settled (Figure 7) and settlement began to occur on less suitable land (Figure 9b-c). This trend continued from 1930 to 1950, when a large influx of settlers settled

Figure 9. The distribution of suitability values remaining available (*i.e.* not previously settled) on the landscape at the beginning of the decade (grey bars) and the proportion of the remaining suitability values settled at the end of each decade (dotted line) where a) 1900-1910, b) 1910-1920, c) 1920-1930, d) 1930-1940, e) 1940-1950 and f) 1950-1960.


a) 1900 - 1910
b) 1910 - 1920
c) 1920 - 1930
d) 1930 - 1940
e) 1940 - 1950
f) 1950 1960
Proportion Available (%)
Proportion Settled (%) of each bar
Suitability Value
5
10
15
20
25
30
35
40
Available to settlers
Settled by settlers

nearly the entire region (Figure 2). This seemingly anomalous period of high increase in settlement is due to the relocation of settlers from the southern prairies to the northern forest during the depression (Fitzgerald 1965). It is during this period that suitability values were settled in relatively equal proportions (Figure 9d-e). By 1950 there was little land still available for settlement (Figure 2), and most of the new settlement occurred primarily in areas of low suitability (Figure 9f).

Figure 10 shows one of the model simulations for the entire study area (using the suitability map Figure 7), the corresponding empirical map of the final year of the simulation (Figure 11), and a map of the differences between the model simulation and the empirical map (Figure 12). The areas that were misclassified were examined using the topographical index (see Figure 15, description below). When simulations were compared to empirical settlement maps, the percent of total cells classified correctly by the model ranged from 44% - 93%, validating that the adjacency algorithm, stoniness, soil type, and soil texture drive the settlement process across the entire study area.

Topographical Index

In an attempt to make the settlement model more general and to explain discrepancies between settlement simulations and empirical data, key physical characteristics of the landscape were incorporated into a topographical index to predict variations in relief and drainage (Beven and Kirkby 1979). Figure 13 shows the variation in relief and drainage for the study area as reflected by the topographic index. In general, low topographic index values occur on ridge

Figure 10. An example of a simulated land use map for 1950 developed by the settlement model for the entire study area using weights developed from a 1930 map of the entire study area.

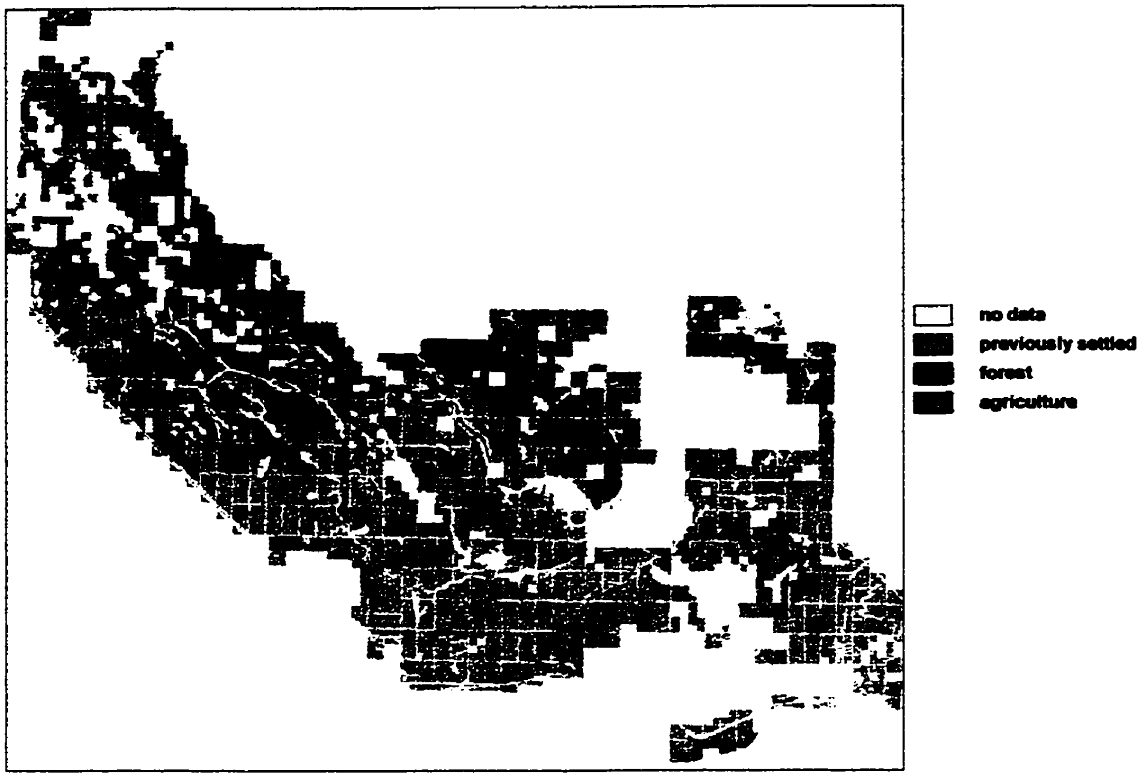

no data
previously settled
forest
agriculture

Figure 11. An example of an empirical land use map for 1950 for the entire study area.

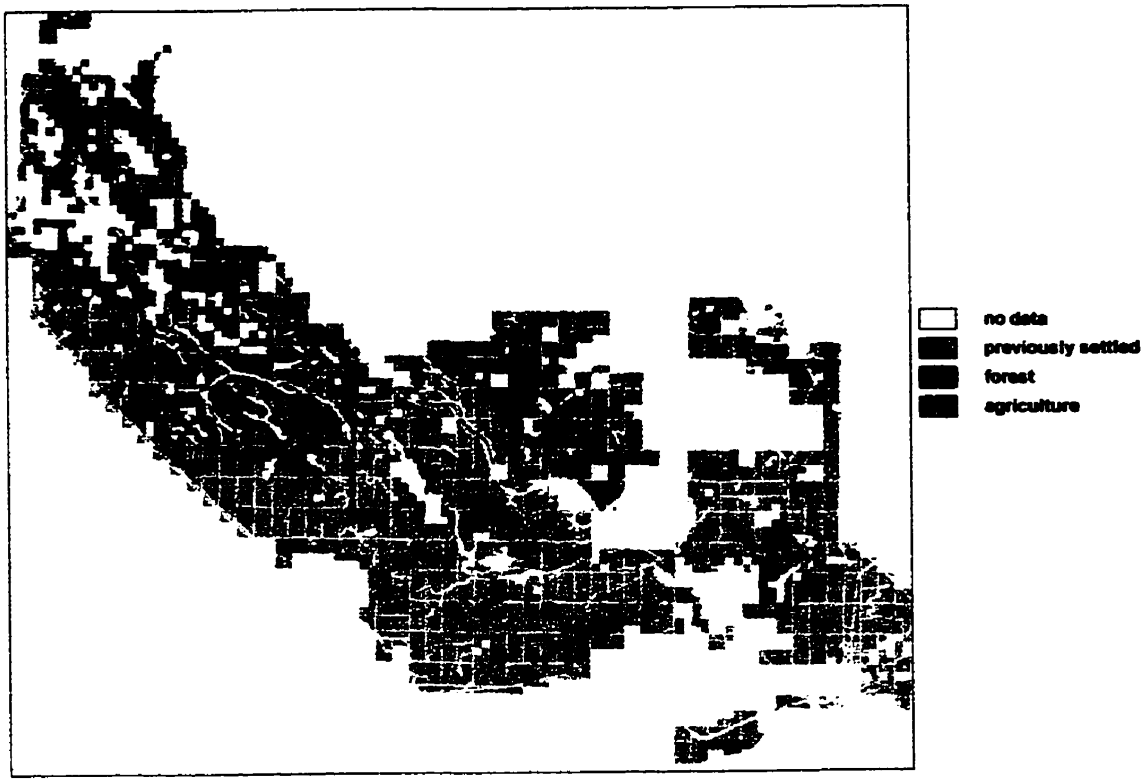

no data
previously settled
forest
agriculture

Figure 12. An example of the difference map showing the locations of the misclassified cells between the 1950 simulated (Figure 10) and 1950 empirical (Figure 11) land use change maps of the entire study area. Red represents areas misclassified by the settlement model as settled and blue represents areas misclassified by the settlement model as unsettled.

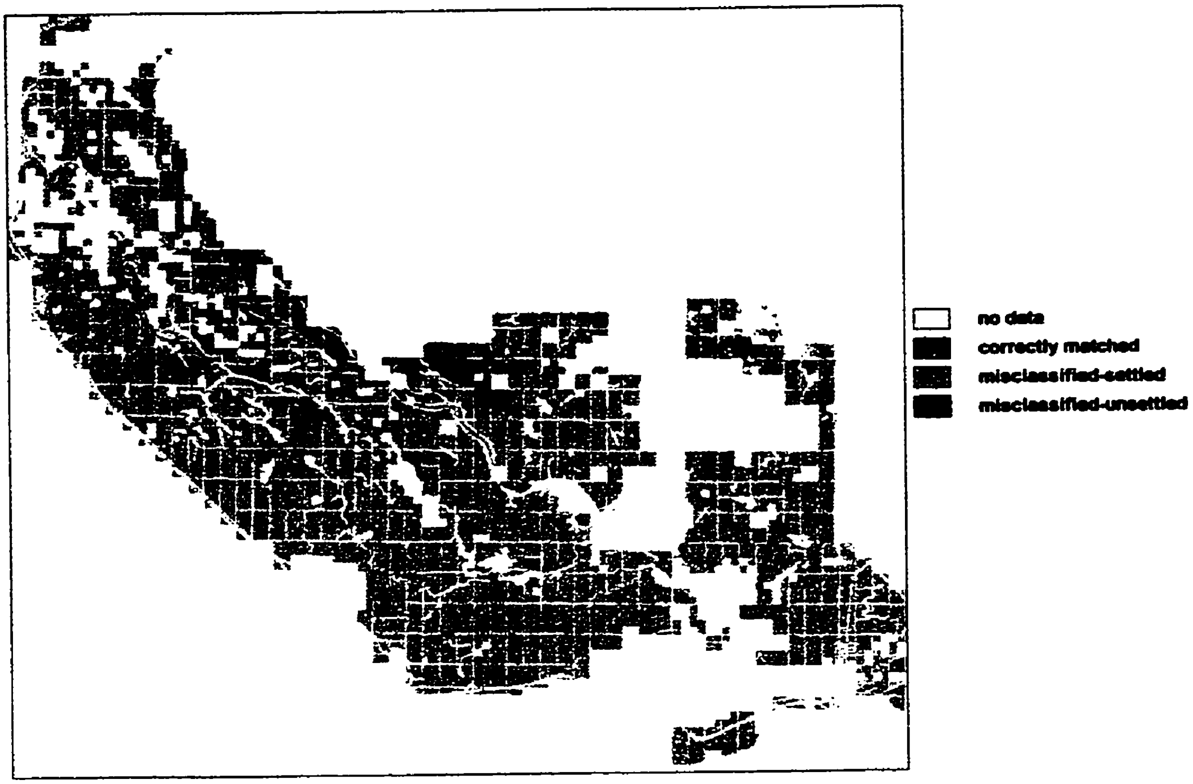
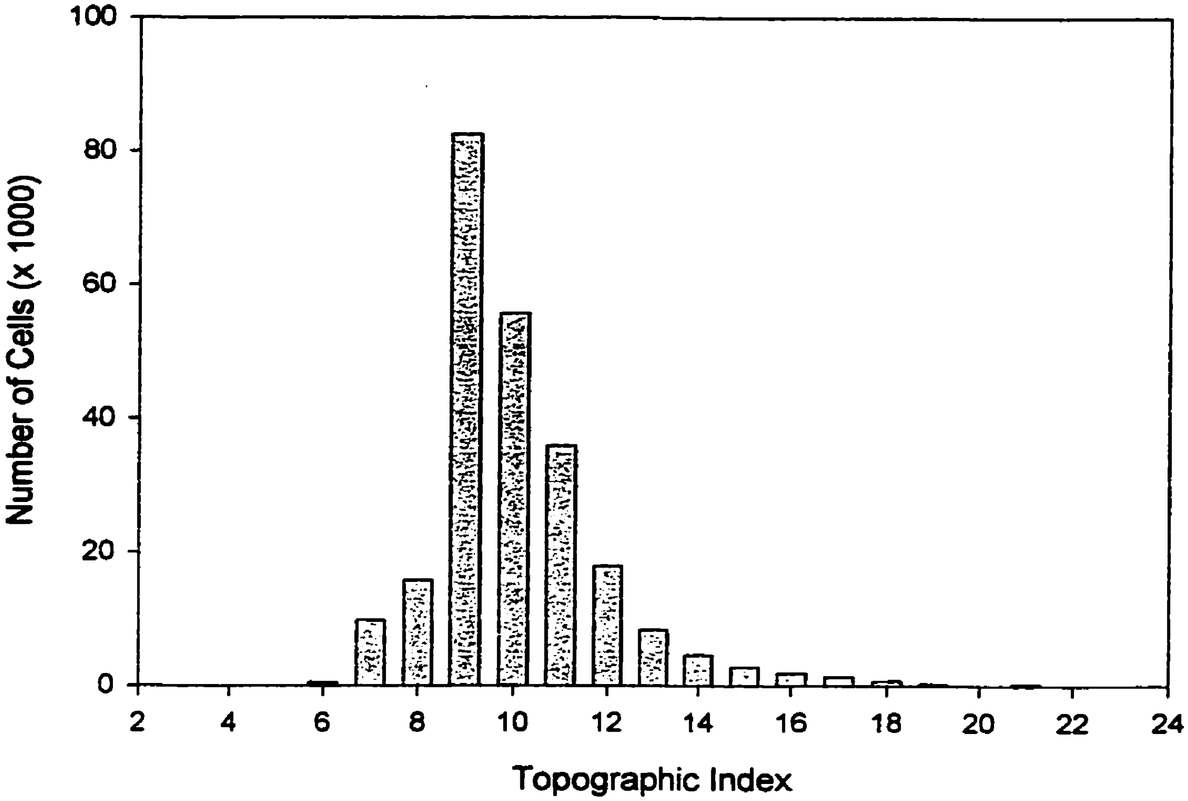

no data
correctly matched
misclassified-settled
misclassified-unsettled

Figure 13. The distribution of the topographic index for the entire study area before settlement (pre-1900).


100
80
60
40
20
0
Number of Cells (x 1000)
2
4
6
8
10
12
14
16
18
20
22
24
Topographic Index

lines, characterized by steeper slopes and smaller contributing areas. High topographical index values occur in depressions, in valley bottoms, or on level terrain with larger contributing areas. That the majority of values for the topographic index in the study area are moderate to high (*i.e.* 9-12 in Figure 13) reflects the subdued topography of the landscape.

The proportion of topographic index values available to the settlers was different than the proportion of topographic index values selected by the settlers for each decade (Table 6). This shows that settlers were selecting specific topographic index values preferentially over others. Figure 14a-f shows the proportion of the topographic index that is settled in a given time period relative to its occurrence on the landscape. In general, from 1910 to 1930 settlers are selecting topographic values in the mid and upper ranges on level terrain (*i.e.* values of approximately 12 - 21 in Figure 14 a-c) and from 1930 to 1960 they are selecting either extreme low or both extreme low and extreme high topographic index values on either ridge lines or valley bottoms, respectively (*i.e.* values of approximately 6-8 and 19-21 in Figure 14d-f).

Comparison of the Settlement Model with the Topographical Index

Figure 15 shows the proportion of the topographic index represented by misclassified cells in the difference map (*i.e.* cells that do not match between the empirical and the simulated maps). The majority of cells that were settled in the empirical map but had low suitability values (*i.e.* classified as unsettled by the model) had low topographic values (*i.e.* 7-9 in Figure 15). The majority of cells that were not settled in the empirical map but had high suitability values (*i.e.*

Table 6. A chi-square goodness of fit test testing if the proportion of topographic index values available to the settlers was independent of the proportion of topographic index values selected by settlers for each decade (χ^2_{crit} =26.296, α=0.05, ν = 17).

Year	χ^2 calculated
pre 1900 - 1900	248
1900 - 1910	52
1910 - 1920	2723
1920 - 1930	402
1930 - 1940	501
1940 - 1950	138
1950 - 1960	321

Figure 14. The distribution of topographic index remaining available (*i.e.* not previously settled) on the landscape at the beginning of the decade (grey bars) and the proportion of the topographic index settled at the end of each decade (dotted line) where a) 1900-1910, b) 1910-1920, c) 1920-1930, d) 1930-1940, e) 1940-1950 and f) 1950-1960.

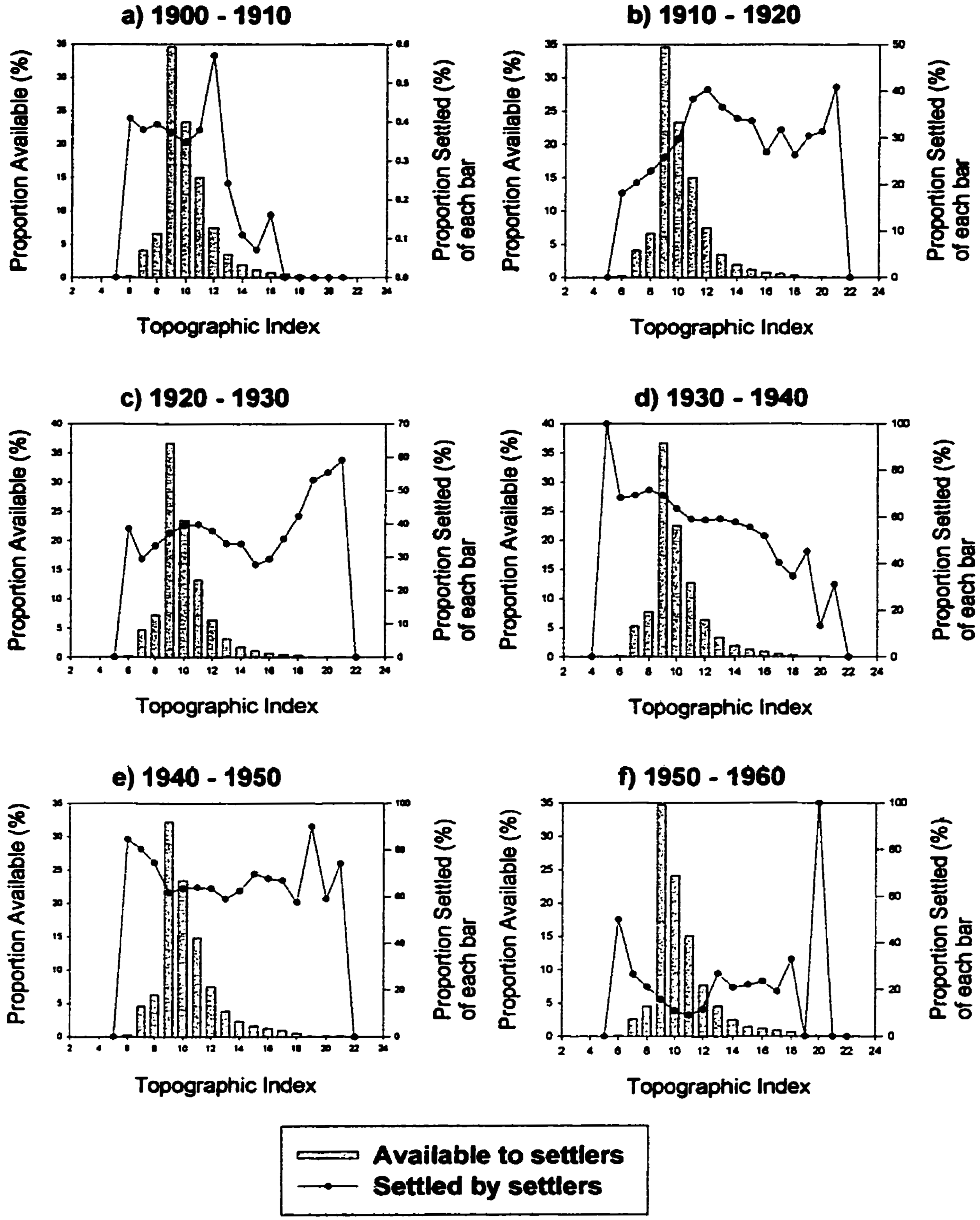
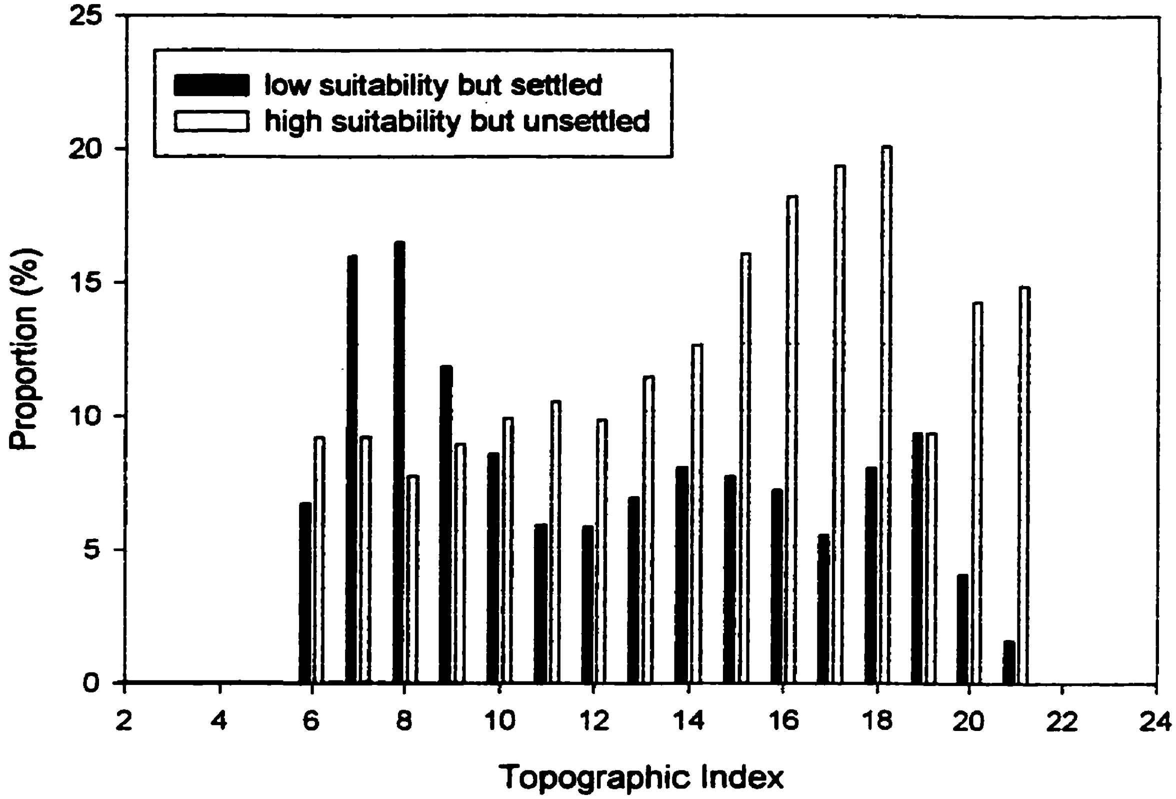

a) 1900 - 1910
b) 1910 - 1920
c) 1920 - 1930
d) 1930 - 1940
e) 1940 - 1950
f) 1950 - 1960
Proportion Available (%)
Proportion Settled (%) of each bar
Topographic Index
Available to settlers
Settled by settlers

Figure 15. The proportion of the topographic index represented by misclassified cells in the difference map of 1950 (Figure 12). Dark grey bars are the areas with low suitability that were settled (areas colored blue in Figure 12) and the light grey bars are areas with high suitability but unsettled (areas colored red in Figure 12).


low suitability but settled
high suitability but unsettled
Proportion (%)
25
20
15
10
5
0
2
4
6
8
10
12
14
16
18
20
22
24
Topographic Index

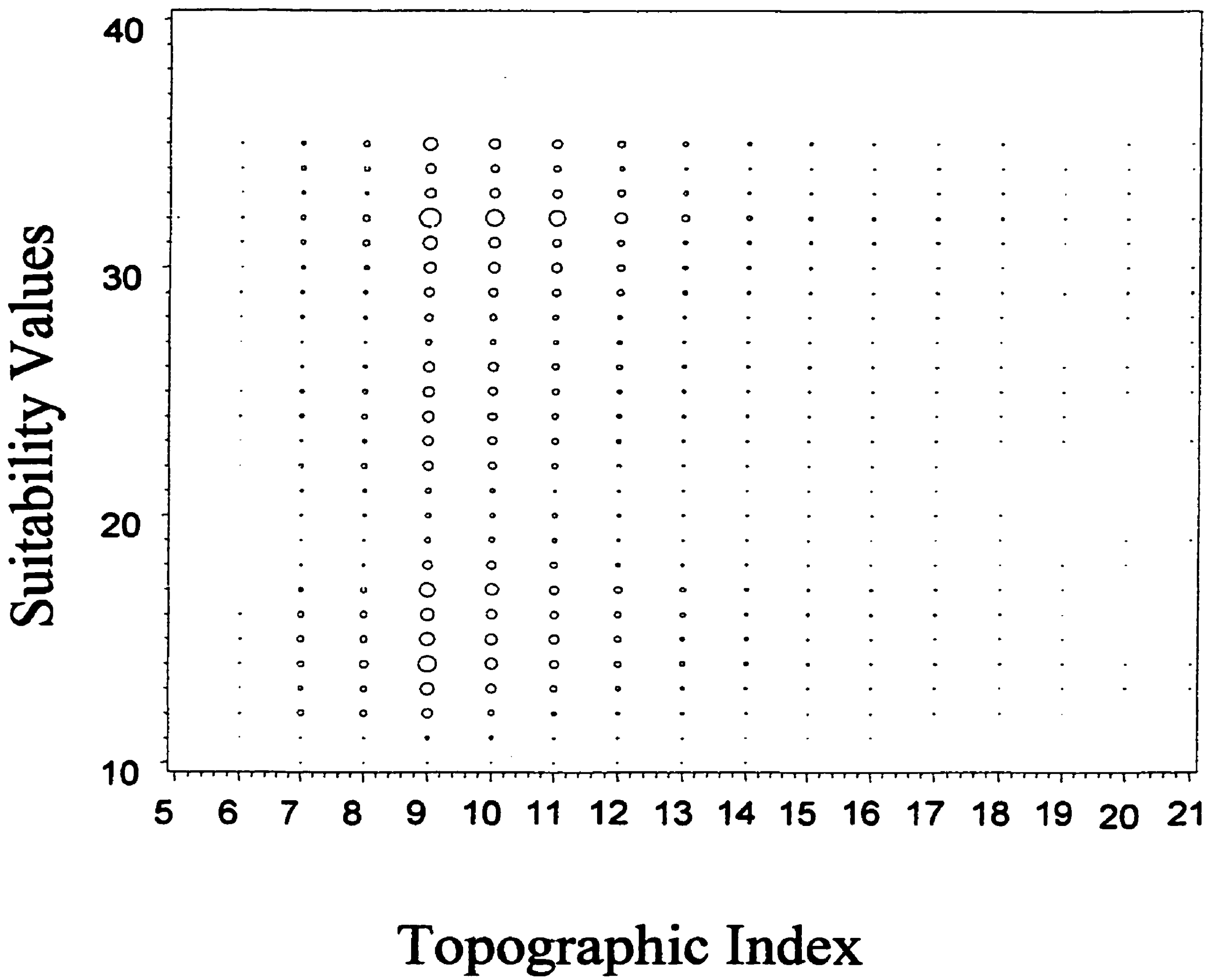
classified as settled by the model simulation) had high topographic values (*i.e.* values from 15-21 in Figure 15).

Figure 16 is an image cross tabulation in which the values for suitability are compared to the values for the topographic index. The size of the bubbles reflects the amount of area in each combination, with the largest bubbles in Figure 16 corresponding to the tri-modal distribution of suitability values (Figure 8). In general, there is a greater range of large bubbles for topographic index values associated with higher suitability values. On the other hand, the range of large bubbles for suitability values of a particular topographic index value decreases as suitability values increase. For example, the range of large bubbles for low suitability values (*i.e.* suitability values of 12-17 in Figure 16) corresponds to a very specific topographic value of 9, while a very specific high suitability value of 32 corresponds to a range of large bubbles for the topographic index (*i.e.* topographic index values of 9-12 in Figure 16). The middle peak occurs over a range of medium sized bubbles for suitability (*i.e.* suitability values of 22-26 in Figure 16) and a range of medium sized bubbles for the topographic index (*i.e.* topographic index values of 9-10 in Figure 16).

DISCUSSION

The most prevalent and persistent type of fragmentation in terms of habitat loss is the large scale clearing of the forest for agricultural settlement (Hudson 1969, Hunter 1996). Studies that implicitly assert that fragmentation is a stochastic process (*e.g.* With and King 1997) are misleading in that settlement activities are not random but instead reflect both the ease with

Figure 16. A comparison of the number of cells classified as a particular suitability value to the number of cells classified as a particular topographic index where bubble size reflects the amount of area in each cross tabulation.


Suitability Values
40
30
20
10
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
Topographic Index

which the landscape can be cultivated as well as the productivity of the land. The results of this study show that the settlement pattern on the landscape is the physical manifestation of the settlement process, and that a simple decision system used by the settlers to clear the landscape of forest can be used to understand the process of fragmentation.

The basic settlement patterns of the Europeans who homesteaded in the study area reveal the conscious selection of cultural and physical elements. The importance of nearest neighbour, stoniness, soil type, and soil texture (Table 1 and Table 3) in determining the pattern of land use change suggests that physical features had a strong influence on the suitability of a particular location for settlement. This seems reasonable, given that the form of agriculture practiced in the study area is mechanized, that the climate and topography does not vary greatly across the region, and that the settlers were privy to only a limited amount of information with respect to landscape variables. Although settlers were able to select which areas to homestead, they had to do so within a survey system that bore no relationship to the productivity potential of the land (Gentilcore 1969, Gentilcore and Donkin 1973, Sebert 1980). Recognizing that the Homestead Acts of 1900-1940 required settlers to cultivate between 15-30 acres of land within 3-4 years of the claim date, it seems reasonable to conclude that settlers would have selected quarter sections that required the least amount of effort to clear and cultivate (Odum 1983, Hall *et al.* 1986, 1995).

Land forms are characterized by distinctive surface expressions, a definite internal structure (composition) and a recognizable shape and nature of surficial materials (Canada Soil Survey

Committee 1978). Therefore, the combination of stoniness, soil texture, and soil formation on the landscape can be used to define specific land forms and identify which areas are suitable for settlement. For example, glaciolacustrine land forms generally consist of fine sand, silt, and clay sediments that have settled from suspension in glacial lakes (Padbury *et al.* 1978). These land forms occur on undulating terrain with very gently sloping topography and tend to be good sites for agricultural settlement (*i.e.* high suitability values in Figure 7). Areas classified as moraines (glacial till) consist of a well-compacted, non-sorted heterogeneous mixture of boulders, gravel, sand, silt and clay that have been transported and deposited by glacial ice (Padbury *et al.* 1978). Moraines are associated with a number of surface forms, ranging from level to inclined, depending upon the materials incorporated into the ice and the manner in which the materials were transported and deposited. Given that stones are almost always present in glacial till deposits, these areas tend to be poor sites for mechanized agriculture (*i.e.* low suitability values in Figure 7).

Distance to transportation networks, which has been shown in other studies to have a strong impact on patterns of settlement because of its importance in moving goods and services (Birch 1967, Nualchawee *et al.* 1981, Sader and Joyce 1985, Ihse 1995, Osborne and Wurtele 1995, Reed *et al.* 1996), did not play a large role in the settlement process here. This is most likely because the relief in central Saskatchewan is gentle (510 to 580 m a.s.l.) and therefore both rail and road transportation routes followed the land survey system. The gentle relief, combined with the fact that most of the study area had been surveyed before the 1900's, meant that many of the transportation routes were in place before the arrival of settlers (Mackintosh and Joerg 1934, 1935, McCormick 1980, Tyrchniewicz 1991, Bantjes 1992). Therefore, land was more or less equally accessible throughout the entire study area. It is expected that in heavily dissected areas characterized by greater topographic relief, the location of transportation networks would be more strongly affected by the topography. In these landscapes, certain areas would be less accessible and therefore less likely to be settled than other areas.

To determine if settlers were basing their decisions on productivity (*i.e.* moisture and nutrient gradients), a topographic index that incorporates the underlying structure of the landscape was used to predict the distribution of water and nutrients on the landscape (Bridge and Johnson 2000). Although settlers did not use such a sophisticated index to determine where to settle, they did use attributes that reflect the underlying structure of the landscape (*e.g.* stoniness, soil texture, and soil formation, Table 1 and Table 3). The topographic index has been shown to realistically predict soil attributes (Moore *et al.* 1993), zones of soil saturation (Sivapalan *et al.* 1987, 1990, Wood *et al.* 1990), water quality problems (Wolock *et al.* 1989, 1990, Robson *et al.* 1992) and variations in surface soil water conditions within a catchment (Band *et al.* 1991, 1993, Quinn and Beven 1993) by redistributing soil water according to hillslope position (Beven and Kirkby 1979, Moore *et al.* 1988a,b).

A previous study of this region (Bridge and Johnson 2000) showed that glaciofluvial and glacial till materials create two very different types of hillslope profiles on the landscape. Hillslopes of glacial till tend to be much steeper, with sudden changes in topographic gradients; while hillslopes of glaciofluvial are flatter with less defined changes in topographic gradients. As seen in this study, glacial till slopes (moraines) also tend to be characterized by low suitability values, while outwash plains of glaciolacustrine and glaciofluvial material have higher suitability values (Table 5). Given the steepness of glacial till slopes (Bridge and Johnson 2000), sudden changes in moisture and nutrients, with not much overlap or range of variation in these values, is expected. In Figure 16, all areas of low suitability (*i.e.* glacial till) are strongly defined by a topographic index of 9. On the other hand, given the variety of materials present on glacial till slopes (a non-sorted heterogeneous mixture of boulders, gravel, sand, silts and clays that have been transported and deposited by ice), a range of relatively low suitability values (*i.e.* values 12-18 in Figure 16) define this single topographic index value.

Glaciolacustrine slopes are comparatively more flat and consist of fine sand, silts, or clays that have settled from suspension. These sediments are well sorted and display stratification. Because hillslopes on these materials are very flat, there are only small differences in topographic index values from ridge lines to valley bottoms. Specific topographic index values are not easily discernable. This, combined with the fact that the landscape is relatively homogeneous with few stones, explains why a single high suitability value of 32 (Figure 16) defines a variety of topographic index values (*i.e.* values 9-12 in Figure 16).

The proportion of topographic index values selected for settlement was different than the proportion of topographic index values remaining available to the settler at the time of settlement (Table 5). Although it appears that settlers are avoiding the topographic index values of 9-11 and choosing sites that fall on either side of these values (Figure 14), there does not appear to be a strong trend of selection for specific topographic values. One reason could be the subdued topography of the study area (*i.e.* the elevation range is only 70 m) and therefore the narrow distribution of wetness values (Figure 11). Given that the crops used by settlers in this region (*i.e.* wheat, oats and alfalfa) are able to tolerate the range of moisture and nutrients (*i.e.* topographic index values) that characterize this landscape (Percival 1921, Matz 1969), it is understandable that the influence of topographic position is not very pronounced. If the area had greater topographic relief or if different types of crops with more specific moisture and nutrient requirements were grown instead, such as safflower (Mündel *et al.* 1992) or corn (Kirk and Harrington 1920), the topographic index might have had a more pronounced influence on settlement.

Another reason that there does not appear to be a strong trend of selection for specific topographic values could be the inability of the settlers to recognize that these topographic index values occur in different positions on different hillslope profiles. Instead, settlers may be choosing the absolute position on the hillslope regardless of substrate simply because certain hillslope positions are easier to cultivate. When the predicted settlement patterns were compared to the empirical settlement patterns, the model predicted less settlement in the north and more settlement in the south. One possible reason for the discrepancy between observed and simulated land use could be the position of these attributes on the hillslope. That is, some settlers may have based their decisions on absolute hillslope position, unaware that a desired topographic value would occur in a different position on a glacial till hillslope than it would on a glaciolacustrine hillslope because of differences in slope and contributing areas. Figure 15 shows that the majority of areas with low suitability values that were settled had low topographic index values (*i.e.* drier sites of steeper slopes and smaller contributing areas). These values tend to occur closer to the ridgeline on glacial till substrates where the slope is steeper and the contributing area is smaller. The majority of high suitability values that were not settled had high topographic index values (*i.e.* comparatively wetter sites of flat slopes and small contributing areas). These values tend to occur further down slope on glaciolacustrine substrate.

Given that these moisture and nutrient values occur in different positions and that these positions vary depending on the profile of the hillslope, some settlers may not recognize that the same position on two different hillslope profiles are in fact characterized by different moisture and nutrient values. In Figure 15, more low topographic index values found in glacial till areas (low suitability value) are being settled than predicted, while not as many high topographic index values found in glaciolacustrine substrate (high suitability value) are being settled. Therefore, it appears that settlers in this study area are choosing lower topographic values (upper slope positions) irrespective of the hillslope substrate (profile). Although the settlement model did perform well in mimicking the spread of settlement from south to north, showing that settlers generally prefer to settle near others on land with fine textured soil and few stones, absolute hillslope position also seems to play a role in determining where settlement will occur. Therefore, settlers appear to be using observable attributes associated with the ease of cultivation to determine the location of settlement.

APPLICATIONS

Habitat fragmentation resulting from agriculture on the landscape is of importance to ecologists since many forested areas are either adjacent to, or influenced by, this man-made disturbance (Fitzgerald 1965, Heinselman 1973, Turner *et al.* 1989b, O'Neill *et al.* 1992, Weir *et al.* 2000). Given that plant species distribution and abundance are affected by moisture and nutrient gradients (Day Jr. and Monk 1974, Whittaker and Niering 1975, Marks and Harcombe 1981, Host and Pregitzer 1992) and that the distribution of moisture and nutrient gradients are in turn determined by hillslope position and surficial geology (Malo *et al.* 1974, Anderson and Burt 1977, Harr 1977, Johnson 1981, O'Loughlin 1981, Sinai *et al.* 1981, Ciha 1984, Bridge and Johnson 2000), an understanding of how settlers use the topographic index to select locations for settlement can be used to predict which native vegetation will be cultivated. For example, settlers in central Saskatchewan were choosing upper slope positions irrespective of the hillslope substrate. Since the occurrence of native vegetation reflects the occurrence of topographic index values on the landscape (*i.e.* top slopes of similar surficial material are drier and poorer in nutrients, while toe slopes are wetter and richer in nutrients), it is predicted that pine and aspen were the first to disappear since these species are found further up slope on glaciofluvial and glacial till hillslopes, respectively (Bridge and Johnson 2000). Considering that birds, animals, and plants are associated with certain habitat types within forested ecosystems, these large scale human fragmentation activities are of particular importance.

CONCLUSION

The settlement model is more desirable than using simple metrics or neutral models to quantify landscape patterns because the process of fragmentation is used to predict which areas will be deforested. Similar to the settlers in the study area who appear to be choosing specific slope positions rather than positions with specific topographic index values, conclusions based on pattern rather than the processes operating behind the patterns are often misleading. In this study I attempt to identify the processes that cause the fragmentation patterns so that land use change could be simulated in a spatially realistic manner and the patterns produced by the fragmentation model understood in terms of the processes producing them. This has important implications for pattern analysis techniques such as FRAGSTAT because the processes producing the patterns can now be linked to the metrics used to quantify them. An understanding about how the patterns are produced can be used to tease out the variability in patterns across different landscapes and gain an understanding of the generality underlying the pattern.

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