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A Markov model of land-use change dynamics in the Niagara Region, Ontario, Canada

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Abstract

Regional Niagara is the site of an intense three-way land-use conflict among urban, agricultural and natural uses. Large scale spatial and temporal land-use data were used to investigate the dynamics of land-use change in this area. A first order Markov chain was used as a stochastic model to make quantitative comparisons of the land-use changes between discrete time periods extending from 1935 to 1981.

The Markov model allowed for two main conclusions about the historic dynamics of land-use change in the Regional Municipality of Niagara.

1. The urbanization of agricultural land was the predominant land-use change.
2. A continuing 'exchange' of land area occurs between wooded and agricultural land-use categories that has little effect on the net amount of wooded land but which could undermine the long-term ecological value of remaining natural areas in Niagara.

Introduction

The Niagara Peninsula is unique in Ontario with a combination of fertile soils and a lake-moderated climate ideally suited for agriculture, especially the production of tender fruit. These same conditions allow the Carolinian assemblage of flora and fauna to exist at the northern limit of its range (Rowe 1977). At one time such forests covered virtually all of the Peninsula.

Due to its climate, soils, water access and strategic location, the 2400 km^2 that makes up Niagara was the focus of intense settlement and clearing by Europeans beginning in the 1700s. Located in southern Ontario between Lakes Ontario and Erie, the Regional Municipality of Niagara now serves as a land link between the conurbations of Greater Toronto/Hamilton (Canada) to the north-west and the Niagara Falls/Buffalo Axis **(U.S.A.)** to the east. Niagara also links shipping between the upper Great Lakes and the Atlantic Ocean by way of the Welland Canal which provides a detour around Niagara Falls.

These and other factors in Regional Niagara make land a valuable and contested resource. To understand the landscape ecology of this area for either theoretical or planning and management purposes it is essential to understand the states and dynamics of land-use. This includes not only the relative amounts of land in different land-use categories but also, more importantly, the dynamics of land-use changes among the categories.

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4 0 4 12 20 Kilometres

Fig. 1. The Regional Municipality of Niagara.

Stochastic models have been used to simulate and explore the entire gamut of dynamic systems including that of land-use change. Bourne (1969) used Markov chains to describe and predict land-use changes inside a city, while Bell (1974) investigated land-use change patterns over the larger area of San Juan Island, Washington. In this study Markovian analysis is used as a descriptive and interrogative tool to understand and quantify the land-use changes that occurred over a human-dominated landscape.

Methods

The land-use data were collected from 1:50 000 scale National Topographic Survey (Canada) maps for 1936, 1952, 1965, 1976 and 1981, *i.e.*, each year that aerial photography updated the cartographic information. Intersections of the Universal Transverse Mercator gridlines provided 1886 sample points within Niagara for each of the map years.

The land-use at any given sample point was classified as either Urban, Agricultural or Wooded according to which use occupied the largest proportion of a circular area extending 250 m in radius around that point. All the sample areas covered entirely by water were discarded since they were all contiguous to either Lake Erie or Lake Ontario and, as such, did not form part of the peninsula proper.

Wooded land was defined as that area symbolized cartographically as forest or in a small number of cases wetland. Agricultural land included areas covered by orchard, vineyard and grassland symbols. Sample points were designated as Urban if the greatest proportion of the area within their sample circles was occupied by one or more of the following map symbols: urban area, airports, parks and golf courses (unless wooded) or mining (both gravel and peat). In addition, points were classed as Urban in two special cases of heavy human impact: 1) if the entire sample area was covered by transportation links (*i.e.*, road, rail); 2) if the sample area included greater than six buildings (This case occurred in less than 0.5% of the sample points).

The problem remains of how to measure land-use change. Categorizing land-use and totalling the number of points per category, per map year is relatively easy. However, "changes" must be measured from some baseline. In the context of this study, land-use change over a time period would be measured using the initial land-use distribution at the beginning of each time period as the 'baseline'. Since land-use distributions are continually changing over time, it follows that the 'baselines' are almost certainly different between time periods. Previous studies indicate that this was undoubtedly the case for Regional Niagara in the 1900s (Krueger 1959; Khan 1980; PALS 1988).

This dependent relationship between the land-use changes in subsequent time intervals has been documented by Bell (1974), Jahan (1976) and Bourne (1976) amongst others. Any direct comparison of the land-use changes that occurred in one time period to the changes in another is statistically invalid. In order to be able to compare the varying land-use distributions over the entire study time-span, the changes that occurred in each discrete time period had to be modelled in such a manner to make them statistically independent of each other.

A first-order Markov model was used to represent the land-use change data for several reasons. Firstly, land-use change is not unidirectional in nature. **A** given parcel of land theoretically may change from one category of land-use, to any other, at any time. Markovian analysis uses matrices that represent all the multi-directional land-use changes between all the mutually exclusive land-use categories. Therefore, with three land-use categories, there are nine possible different land-use changes which are incorporated into a nine cell transition matrix for each discrete time period.

Secondly, repeated iteration of the transition matrix results in a second matrix (equilibrium matrix or primary eigenvector) that is representative of the land-use changes during the time period, but has transformed the values in such a manner that they have become independent of the starting land-use distribution of that time period. This 'matrix-powering' (Bourne 1976) allows the inter-period comparison of changes that were statistically impossible before.

Thirdly, the 'matrix-powering' condenses the 9 cell transition matrix into an equivalent 3 cell matrix. The values in the three cells represent the amount of each land-use category at a hypothetical future equilibrium. The hypothetical equilibrium is based on the unrealistic assumption that the transition matrix remains constant *i.e.*, land-use change is constant. It is not implied that this 'equilibrium' will ever be reached. Rather, the equilibrium distribution serves to illustrate clearly the process of land-use change between time periods.

Since each period has an equilibrium matrix **(Q)** representative of the land-use changes during that time, and the matrices are now independent, calculations using the equilibrium matrices yield quantitative information about land-use change that can then be compared among the time periods.

The Markov chain equation was constructed using the land-use distributions at the beginning **(M,)** and at the end of a discrete time period as well as a transition matrix ($\mathbf{M_{LC}}$) representing the land-use changes that occurred during that period. The matrix cell values are derived directly from topographic maps and expressed as proportions. Under the assumption that the sample is representative of the region, these proportional changes become probabilities of land-use change over the entire sample area and form the transition matrices.

The three matrices created above were then assembled to form a 'link' in the Markov chain using the following equation:

Where U_t represents the probability of any given point being classified as urban at time t, and LC_{ua} represents the probability that an agricultural point at t will change into urban land by $t+1$ and so on.

Iteration of this matrix equation derives the equilibrium matrix **Q** which by definition occurs when the multiplication of the column vector (land-use distribution) by the transition matrix yields the original column vector. *i.e.*, $\mathbf{M_{LC}}$ * **M,** = = $\mathbf{M_t}$

Results and discussion

To apply the Markov model to time series data one must first demonstrate that land-use change in Regional Niagara during the study period was not random. **A** simple **3-by-3** contingency table was used with the Chi-squared statistic to test the null hypothesis that the land-use distribution obtained from one map year was independent of the distribution on the previous or subsequent years. The test-statistic was significant for each comparison ($p << 0.001$ at $df = 4$). The probability of making a Type I error regarding the hypothesis was highly unlikely. The rejection of this null allowed further Markovian analysis.

The proportion coverage of Niagara by each of the three land-use categories is shown in Table 1 for each map year. The general trends observed are, for the most part, a quantitative expression of what was expected based on accounts in the literature. Specifically, Niagara experienced a 13% drop in agricultural lands since 1936, which translates into over one tenth of Regional Niagara's total area being taken out of agricultural production. Other studies show that this loss occurred primarily in those areas best suited for agriculture, magnifying the deleterious effect (Krueger 1959, 1982; Krushelnicki and Bell 1989). Conversely, the total amount of urban land has increased fourfold during the 45 years studied while the amount of wooded land remained nearly constant (Table 1).

The theoretical land-use distributions generated through the Markov model revealed quite different trends. It must again be emphasized that the Markov values, or equilibrium matrices, do not represent realistic future states for Niagara. Rather, they are direct equivalents of the land-use changes that occurred in a given time period (*i.e.*, the transition matrices) and because of their new mutual independence may be compared directly. For the purposes of clarity and brevity, the adjective "Markovian" will differentiate these values (Table 3) from the actual land-use distributions found in Table 1.

Two different trends emerge from these data before and after 1952. The land-use distribution in first study period (1936–52) Markovian urban area dominates both of the other land-use categories. It

Table 1. Proportional area in each of the land-use categories for Regional Niagara. (n= 1886)

	1936	1952	1965	1976	1981
Wooded	0.14	0.12	0.12	0.12	0.13
Agricultural	0.82	0.81	0.77	0.74	0.71
Urban	0.04	0.07	0.11	0.14	0.16
Totals	1.00	1.00	1.00	1.00	1.00

Table 2. Totals for each type of land-use change in Regional Niagara for each time period.

	1936–52	1952–65	1965–76	1976–81
Wooded — Wooded	195	161	178	198
Wooded – Agricultural	63	50	35	29
Wooded — Urban	1	15	10	6
Agricultural – Wooded	31	59	51	38
Agricultural – Agricult.	1470	1392	1338	1301
Agricultural – Urban	40	84	65	49
Urban — Wooded	0	3	4	5
Urban – Agricultural	2	12	15	10
Urban – Urban	84	110	190	250
Totals	1886	1886	1886	1886

Table 3. Markovian modelled, theoretical land-use distributions (proportional equilibrium values) for Regional Niagara for each of the time periods.

	1936–52	1952–65	1965–76	1976–81
Wooded	0.04	0.10	0.13	0.14
Agricultural	0.45	0.58	0.54	0.49
Urban	0.51	0.32	0.33	0.37
Totals	1.00	1.00	1.00	1.00

reflects a time when a high rate of urban expansion coincided with very low losses of urban land over the Regional Municipality of Niagara. The relatively high level of Markovian agricultural land seems to have been the result of the high rate of wooded area being converted into agricultural use (see Table 2).

Land-use changes after 1952 reveal a consistent pattern of Markovian urban and wooded lands gradually increasing at the expense of the amount of Markovian agricultural land. The net gain by the woodland was not so much a consequence of natural regeneration but rather a decrease in the rate at which woods were being cleared. Any continuing gain of wooded area seems to have been arrested, replaced by a proliferation of urban uses.

By examining the detailed land-use change data in Table 2, it became evident that the urbanization of agricultural land was one of the driving forces resulting in the general trends in land-use change described above. Aside from the changes occurring along the primary diagonal of the transition matrix (non-changes *e.g.*, wooded to wooded), agricultural to urban land-use changes were the most frequent (except in 1936–52). The phenomenon of development on prime Niagara farmland has been recognized for over 50 years (see Krueger 1959), yet the results of present regional government efforts to protect these areas are as of yet uncertain (Regional Municipality of Niagara 1988; PALS 1988; Niagara Region Review Commission 1989).

The second non-obvious relationship that appears out of the land-use change data (Table 2) involves agricultural and wooded lands. There is an 'exchange' of area, nearly equal in magnitude, that results in little net change in the total areas of either category. The minor variances in the total amounts of land conceals this exchange when the simple land-use distributions are examined (Table 1). While the sum of the changes is near zero, and thus the amount of wooded land remains the same, the land-use changes have serious ramifications for the preservation of wooded areas in Niagara. Between 13% and 26% of wooded land was agricultural land in the previous time period. These woodlands regenerating from agricultural use are almost certainly not climax Carolinian vegetation, but rather they are colonizing, generalist and edge-type species with less conservation value in the Niagara context. It should be noted, however, that the wooded areas being cleared are not necessarily mature forest, but with only 13% of Regional Niagara left forested every piece of remaining woodland is important ecologically. The situation is even more alarming since the 13% figure includes wetlands and forest fragments as small as 0.07 km^2. Virtually all of the wooded area in Regional Niagara would need to be designated as parkland or reserve to meet the 12% target subscribed to by both the Ontario and Canadian governments, following the recommendations of the Brundtland Commission (World Commission on the Environment and Development 1987). On a positive note, at least the Markovian trends show that the net change into woodlands is increasing very slightly rather than decreasing.

Conclusions

The Markov model provided a simple methodology by which a dynamic system could be dissected and examined. In addition to quantifying the land-use changes that occurred, this procedure was able to reveal non-obvious trends in the data.

For Niagara, and Canada, the prime concern must be the rate at which a valuable agricultural land base continues to be replaced primarily with urban development. While the amount of urban land continues to increase in Niagara, of greater concern is the continuing increase in the rate at which land is being converted into urban uses as shown by the Markov model.

The small amount of area covered by wooded land remained fairly constant, and indeed the Markovian analysis indicated that over the entire study period the rate at which woodland was being cleared eased slightly. Unfortunately, ecological degradation of the remaining woodlands could result through a continuing exchange of agricultural and wooded lands.

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