SIMULATING LAND USE CHANGE AND ENVIRONMENTAL IMPACTS

Li-Ta Hsu and Walter L. Mills, Jr.[1]

ABSTRACT.—A binary-logit probit model of the conversion of farmland and forestland to urban use was estimated. This land use choice model was then used to simulate future land use changes under different scenarios. Factors considered in the models included soil characteristics, location, land tenure, size of parcels, zoning and other regulation, and level of urbanization. Spatial data and relationships are modeled in the land use choice model by including soil conditions, proximity to urbanized areas, and travel time. Five scenarios—basic, wetland protection, riparian protection, traffic improvement and equal probability of development—were simulated.

INTRODUCTION

Maintaining healthy ecosystems and protecting the earth's biological diversity has recently aroused significant concerns (Costanza et al. 1992). Scientific evidences suggest that the present-day extinction rate is at least hundreds of times higher than the long-term natural rate (Myers 1988); and, if current trends continue, 2.5 percent to 15 percent of all species on earth could be lost over the next decade (Primack 1993). Among the many factors contributing to loss of biological diversity, the most threatening one is loss of habitat (Primack 1993). Alteration of natural environment by human activities has caused unprecedented loss of species and degradation of ecosystems. Human activities such as farming, ranching, and urban development have converted natural landscapes into mosaics of natural vegetation within matrices of human-dominated land uses and have had a profound impact on species and ecosystems (Adams 1994).

From humans' perspective, however, alteration of natural landscapes reflects their need for food, shelter, and many other natural resources (Barlowe 1978). Humans respond to these needs under various natural, economic, and social constraints and behave to increase both economic and sociocultural well-being (Rebisame et al. 1994). As a result, human land use patterns that affect ecological phenomena or alter the natural environment are driven by a variety of social processes (Rebisame et al. 1994). Therefore, to better understand the impact of land use change on terrestrial ecosystems, the social processes and factors affecting human land use must be more fully studied (Machlis and Forester 1996). In recognition of the importance of social processes, the National Research Council stated that "biological diversity has been lost as a result of social processes, and will ultimately be conserved only through adjustments in these processes. Unless and until they are understood, there is little lasting hope for conservation" (National Research Council 1992, page 8). The Nature Conservancy, in its Last Great Places initiative, also recognized that "the continued success of our efforts to preserve biodiversity in the face of mounting threats will depend on our ability to integrate socioeconomic factors into our conservation equations" (Watson 1994, page 33).

OBJECTIVES

The socioecological interrelationship has been widely recognized, and several conceptual models have been developed to depict the complex interactions between humans and the natural environment (e.g., Messerli and Messerli 1978; Vink 1983; Turner et al. 1994). These models generally recognize the importance of social forces on the natural environment and interpret landscape or land use as the interface between natural and social processes. In van Langevelde's (1994) framework, landscapes should be perceived as the total spatial and functional entity in which social processes or human practices interact with natural processes. Turner et al. (1994) indicated that there is a crucial need for a better understanding of the human forces driving ecological change. However, until recently,

[1] Li-Ta Hsu, Graduate Research Assistant, and Walter L. Mills, Jr., Associate Professor, Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47907. Dr. Hsu is currently teaching in Taiwan (Email: lita@mail.ht.net.tw).

studies on the subject of socioecological interaction rarely go beyond conceptual discussion (Machlis and Forester 1996).
To make the conceptual models operational, a practical methodology is necessary. The recognition of land use as the socioecological interface leads to the need for land use study. Land use study is an interdisciplinary research field related to ecology, geography, economics, and sociology. Studying the processes of land use and land use change can help to understand the connection between social processes and the natural environment. Therefore, the objectives of this study are:

1. To study the processes of human land use and to develop models for explaining and predicting land use changes.

2. To present a method that integrates human land use processes and environmental or ecological impacts.

To illustrate the proposed methodology, an analytical framework was applied to a case study of an urbanizing watershed. The case study focused on landscape changes resulting from urbanization. Urbanization has been described as a "convenient shorthand for the ecological forcing functions created by the growth of cities and associated human activities" (McDonnell and Pickett 1990, page 1232). Ecologically, urban areas are effectively synonymous with ecosystem disruption and erosion of biological diversity (Murphy 1988). From a sociological perspective, urbanization also represents a complex social process closely associated with many other social issues such as employment, welfare and poverty, education, and crime (Mills 1972; O'Sullivan 1990).

PROCEDURE

Study Area

The study area is a small watershed adjacent to the western boundary of West Lafayette in Tippecanoe County, Indiana. The watershed covers 27.8 square miles and Indian Creek flows 10 miles from north to south into the Wabash River. In order to obtain landowner property boundaries, the public land survey system of sections and townships is used to approximate the watershed boundary. The study consists of the 41 sections.

Land uses in the study area were classified into three categories: agricultural, urban, and public and others. Although agriculture has been the dominant land use, urban influence is spreading westward from the city of West Lafayette. The percentage of urban land uses increased from 8 percent in 1989 to about 12 percent in 1995. Urban land uses were primarily residential; industrial and commercial developments were relatively few. The category "public and others" includes areas designated for public services such as parks, golf courses, utilities, and cemeteries. It also includes 2,059 acres of land held by Purdue University

Data collection

Data collected for the empirical analysis came mainly from the geographical information system (GIS) database of Indian Pine Natural Resources Field Station, property records maintained by Tippecanoe County Offices, and the soil survey of Tippecanoe county from the Natural Resource Conservation Service of the United States Department of Agriculture. The Indian Creek watershed is one of the watersheds within the boundary of the Purdue Indian Pine Natural Resources Field Station. The Indian Pine Natural Resources Field Station was organized in 1989 by Purdue University to examine ecological processes in human dominated landscapes. The GIS database contains digitized maps (mostly in 30 by 30 meter resolution) including ownership boundaries and other spatial data. The GIS ownership boundaries were matched with the property records maintained by Tippecanoe County. As of December 1995, a total of 2396 land parcels were identified within the study area. The property records were then traced back to the year 1989 to identify any land use change during the period of 1989 and 1995. Subsequently, 631 agricultural land parcels were identified as present in 1989. Among them, 127 (or 20 percent) of the parcels were either converted to urban uses or idled awaiting for urban development during the observed six-year period.

From the 631 agricultural land parcels (as of 1989), 250 were selected for more detailed data collection. To maintain representative proportions observed in the overall agricultural parcels, 50 parcels (20 percent of the 250 parcels) were randomly selected from those parcels that switched all or part of the parcel to urban use during 1990 and 1995.

The other 200 parcels were randomly selected from those parcels that remained in agriculture throughout the observed period.

Characteristics of land ownership including parcel size, frequency of land transfer, existence of land improvement, address of the landowner, and zoning regulations for the 250 sample parcels were collected from county property records. Regional development trends were represented by the total housing units in West Lafayette and its fringe areas. Local development trends were summarized as the percentage of urbanization in a section and a quarter-section based on the property records. Land characteristics and spatial attributes such as soil productivity, building suitability, acreage of woodland in the parcel, traffic time to the nearest business center, and accessibility to sewer systems were derived from the GIS database. As a result, data for the 250 parcels at 6 points in time were established. The land use data and the observed variables of the 1500 observations (250 parcels times 6 years) were subsequently used to examine the relationship between the urbanization decision and the characteristics of land and land ownership. Table 1. summarizes the definitions of variables and their expected effects on urbanization.

Table 1.—Explanatory variables and their expected effects on urbanization

Variable	Expected Influence	Definition of Variables
TIME	-	Traffic time to the nearest business center (in minutes)
SEWER	+	Whether the parcel is within 1000 feet of sewer systems (1=Yes, 0= No)
PROD	-	Soil productivity of the parcel (in bushels of corn per year)
BLDG	+	Building suitability of the parcel
IMPROV	+	Existence of land improvements (1=Yes, 0= No)
FOR	+	Acreage of woodland in the parcel
SEC	+	Percentage urbanized in the section
QTR	+	Percentage urbanized in the quarter section
DWELL	+	Number of dwelling units in West Lafayette and its fringe areas
URBAN	+	Whether the parcel is located within the urbanizing boundary (1=Yes, 0= No)
ZONING	?	Whether the parcel is zoned for urban uses (1=Yes, 0= No)
ACRE	-	Acreage of the parcel
TRANS	+	Number of land transfers since 1981
ADDR	?	Whether the landowner lives in Tippecanoe county (1=Yes, 0= No)

Analytical Framework

The first step in this study was to develop a land use choice model for explaining observed urbanization pattern and predicting future urbanization probabilities for agricultural land. The land use choice model assumed that landowners make land use decisions by maximizing their utilities from land uses. That is, an agricultural land will be converted to urban uses if the landowner perceives a higher satisfaction from converting to urban uses than remaining in agriculture use. The utility functions of different land uses were assumed to be dependent on a set of observed variables and other unobserved random errors. A binary logit model was used to empirically derive the relationships between urbanization decisions and the observed explanatory variables. Factors examined are those listed in Table 1. The binary logit model was specified as

[1] $$y^*_{it} = b' x_{it} + e_{it} \; (i = 1 \ldots 250,\; t = 1 \ldots 6)$$

where y_{it} is the land use choice ($y_{it} = 1$ if the parcel was urbanized and $y_{it} = 0$ if the parcel remained in agriculture), and y^*_{it} denotes the utility differences between urban uses and agricultural uses ($y_{it} = 1$ if $y^*_{it} > 0$ and $y_{it} = 0$ otherwise). x_{it} is a vector of observed exogenous variables relevant to land use utilities. x_{it} is a vector of parameters associated with the exogenous variables. e_{it} is an unobserved random error term. Assuming the relationships continue to hold in the future, the binary logit model can be used to predict urbanization probabilities of the remaining agricultural parcels. The urbanization probability of land parcel *i* at time *t* is

[2] $$P_i = \frac{\exp(b' x_{it})}{1 + \exp(b' x_{it})}$$

The second step of the case study was to project urban growth in the study area for the next 10 years. Housing-unit growth from 1989 to 1995 in West Lafayette and its fringe areas were fitted with regression-based growth projection models to estimate the growth rate, and to test whether the arithmetic growth model or the exponential growth model is more appropriate. The results showed that West Lafayette and its fringe areas had an arithmetic growth trend with an estimated annual growth rate of 1.745 percent. The same growth rate was used to project future urban development in West Lafayette and its fringe areas. Future urban development in the study area was projected using a ratio-based technique that predicts the urban development in the study area as a proportion of the urban development in West Lafayette and its fringe areas. Based on the property records of the study area, the ratio increased from 8.1 percent in 1989 to 9.7 percent in 1995, and is expected to increase to 12.3 percent in 2005 if the trend continues. Table 2 shows the projected urban growth in West Lafayette and its fringe areas, and for the study area from 1995 to 2005.

Table 2.—Projected regional housing developments and housing units within the study area

Year	West Lafayette and its fringe areas	Study area
1995	17261	1676
1996	17534	1748
1997	17806	1822
1998	18079	1897
1999	18351	1974
2000	18624	2052
2001	18897	2132
2002	19169	2213
2003	19442	2295
2004	19715	2379
2005	19988	2464

The third step of the study was to allocate the projected urban growth spatially and temporally to the study area. The estimated binary-logit land use choice model was used to predict the urbanization probabilities of the remaining agricultural parcels in the study area. Parcels to be urbanized were selected based on the relative probabilities of the parcels. Parcels with higher urbanization probabilities are more likely to be urbanized. The urbanization probabilities were updated in each year of the simulations. Since urbanization of any land parcel was only known probabilistically, different runs of the simulation would generate different urbanization patterns. Therefore, the simulation process was repeated 1000 times to generate distributions of simulation results.

Urbanization impacts including acreage of forests and wetlands affected by urbanization, changes in annual agricultural production, and urbanization impacts on surface-water run-off were also monitored in the simulated urbanization process. Forests and wetlands affected by urbanization were derived from the simulated urbanization patterns and maps of existing forests and wetlands. There are about 3,280 acres of forests and 709 acres of wetlands in the remaining agricultural land. Changes in agricultural production were derived from the acreage of croplands being urbanized and soil productivity. Effects on surface-water run-off were evaluated in terms of changes in the curve number of the watershed. The watershed currently has a composite curve number of 77. The curve number is an empirical overall rating of land based on soil hydrologic grouping and land use. It can be combined with long-term climatological data to predict surface-water run-off from given rainfall depths (USDA SCS 1986, Harbor 1994).

To compare urbanization impacts under different situations, five land use scenarios were simulated.

1. A **basic** scenario simulating urbanization patterns under existing conditions;
2. An **equal-probability** scenario that assumes that all parcels have the same probability of being urbanized and results in uniformly random urbanization patterns. This scenario was used to compare the differences between uniformly random urbanization patterns and patterns based on the predicted urbanization probabilities.
3. A **wetland-protection** scenario protects remaining wetland by prohibiting urban development.
4. A **riparian-protection** scenario protects stream and riparian areas by restricting urbanization within a 100-foot riparian buffer zone. Parcels affected by the buffer zones were mainly those adjacent to the upper streams because riparian zones in the lower section of the watershed were generally zoned as flood plains where urban development is already prohibited
5. A **traffic-improvement** scenario modeling proposed traffic improvements in the southern part of the watershed. The traffic improvement changes the travel times, increasing urbanization probabilities.

RESULTS

Parameters of the binary-logit model were estimated using the maximum likelihood method. Several variables were found to have diminishing influences on choice probabilities. For these variables (ACRES, FOR, SEC, TRANS), square-root or logarithm transformations were made to account for the diminishing effects. Multicollinearity between variables was found to be an estimation problem in the logit model. There was a high correlation between traffic time (TIME) and urbanizing boundary (URBAN), between soil productivity (PROD) and acreage of woodland in parcel (FOR), and between zoning (ZONING) and sewer accessibility (SEWER). As a result, some of the estimates of the coefficients in the full model were biased. Therefore, three of the explanatory variables (URBAN, PROD, and SEWER) were excluded so that the influences of the remaining variables might be determined. The estimation results of the logit model were shown in Table 3.

Table 3.—Estimation results of land use choice models

Variables	Parameter estimates	Asymptotic t-statistics
Constant	-10.478	-2.493
TIME	-0.18663	-3.254
BLDG	1.9405	4.960
IMPROV	0.44667	2.050
SQRT(FOR)	0.39065	4.620
SQRT(SEC)	-0.41405	-3.768
SQRT(QTR)	0.36257	5.387
DWELL	0.62941	2.420
ZONING	-0.58038	-2.219
ln (ACRE)	-0.91640	-6.069
SQRT(TRANS)	1.3709	6.595
ADDR	1.1819	2.985
Likelihood Ratio Test Statistic	329.133	
Likelihood Ratio Index (ρ^2)	0.3453	

Measures of the goodness of fit indicate that the model fit the data fairly well. The likelihood ratio test statistic, which is asymptotically distributed as χ^2 with K degrees of freedom (K = number of parameters being estimated), rejected the null hypothesis that all the parameters are zero, suggesting that there is a relationship between the urbanization probability of a parcel and the explanatory variables. The likelihood ratio index (ρ^2) is an informal goodness-of-fit index that measures the fraction of an initial log-likelihood value explained by the model. ρ^2 ranges from zero, when the estimated parameters are no better than zero parameters, to one, when the estimated parameters allow for perfect prediction of the observed choices. However, the likelihood ratio has no intuitively interpretable meaning for values between the extremes of zero and one, and there are no general guidelines for when a ρ^2 value is

sufficiently high. Nevertheless, when comparing models estimated on the same data and with the same set of alternatives, it is usually valid to say that the model with higher ρ^2 fits the data better.

The effects of explanatory variables in general agree with the a-priori expectations. Results of the logit land use choice model indicate that several factors might have contributed to the observed urbanization patterns of agricultural land in the study area. Large parcels and parcels farther away from business centers were less likely to be urbanized. Parcels with land improvement or higher building suitability, parcels containing large acreage of woodlands, parcels owned by local landowners, and parcels undergoing frequent land transfer were more likely to be urbanized. Regional and local development trends also positively contributed to urbanization decisions. Probability of urbanization increased as the percentage urbanized in a quarter-section increased, but the effect diminished as the section became more densely developed. Zoning was found to have a negative effect on urbanization decisions, suggesting that speculation existed in areas zoned for urban uses. The speculation effect explains the leapfrog urbanization pattern found in the study area.

Based on the simulated urbanization patterns, urbanization impacts under each scenario were evaluated. Table 4. summarizes the means of urbanization impacts under different simulation scenarios. Duncan's multiple-range tests (Duncan 1955) were used to perform pairwise comparisons to test whether the means are significantly different between the scenarios.

Table 4.—Comparison of urbanization impacts under different simulation scenarios

Means of impact (with 1000 simulations)	Basic scenario (B)	Wetland protection (W)	Riparian protection (R)	Traffic improvement (T)	Equal probability (E)	Duncan's[a] multiple range test[b]
Acreage of urbanization (acres)	2,077.76	2,077.76	2,070.95	2,097.69	2,159.33	R<u>BW</u>TE
Forests affected by urbanization (acres)	611.38	575.47	593.92	611.53	370.46	EWR<u>BT</u>
Wetlands affected (acres)	62.49	0	58.26	60.99	38.73	WERTB
Agricultural reduction (1000 bushels of corn)	169.26	173.29	170.58	171.19	220.12	BRTWE
Decreases in watershed curve number	0.531	0.553	0.537	0.530	0.660	<u>TB</u>RWE

[a] DUNCAN, D.B. 1955. Multiple range and multiple F tests. *Biometrics*. 11:1-42.
[b] Scenarios are listed from left to right in ascending means of impact; scenarios whose impacts are not significantly different are underlined.

Figure 4 compares the distributions of urbanization impacts of the five land use scenarios. Environmental impacts of the equal-probability scenario appear to be significantly different from the others. That is, if different parcels do have different urbanization probabilities, ignoring such differences would significantly overestimate the total urbanization acreage as well as changes in agricultural production and curve number, while underestimating urbanization impacts on forests and wetlands. Some of the environmental impacts of other scenarios are also statistically different from those of the basic scenario. Protecting wetlands from urban development would significantly reduce urbanization impacts on forests, wetlands, and curve number, but at the expense of greater agricultural loss. Riparian protection also has similar effects, but the effects are less significant. Proposed traffic improvement, if completed, would increase urbanization acreage, slightly decrease impacts on wetlands, slightly increase agricultural loss, but would not significantly affect impacts on forests and changes in curve number. However, forests affected by urbanization in the basic scenario and traffic improvement scenario have different spatial patterns although they are quite similar in terms of acreage.

CONCLUSIONS

Several conclusions can be drawn from the findings of this case study. First of all, land use patterns in human-dominated landscapes are not completely random. Land use patterns not only depend on characteristics of land, but also depend on land use regulations, regional and local development trends and characteristics associated with landowners. Second, different land parcels have different land characteristics, and they may be owned by different landowners or subject to different land regulations. As a result, different land parcels may have different probabilities of land use change. Failure to account for the probability differences may result in erroneous predictions of land use patterns and land use impacts. Third, human behavior is inherently probabilistic, and, as such, land use patterns in human dominated landscapes can only be predicted probabilistically. However, with the probabilities of land use change derived from land use choice models, likely land use patterns and distributions of land use impacts can be simulated using repeated simulations. The simulation approach can be used to incorporate ecological or environmental assessment with human land use activities, and is useful in comparing the effects of different land use control strategies and in deriving the relationships between land use changes and land use impacts.

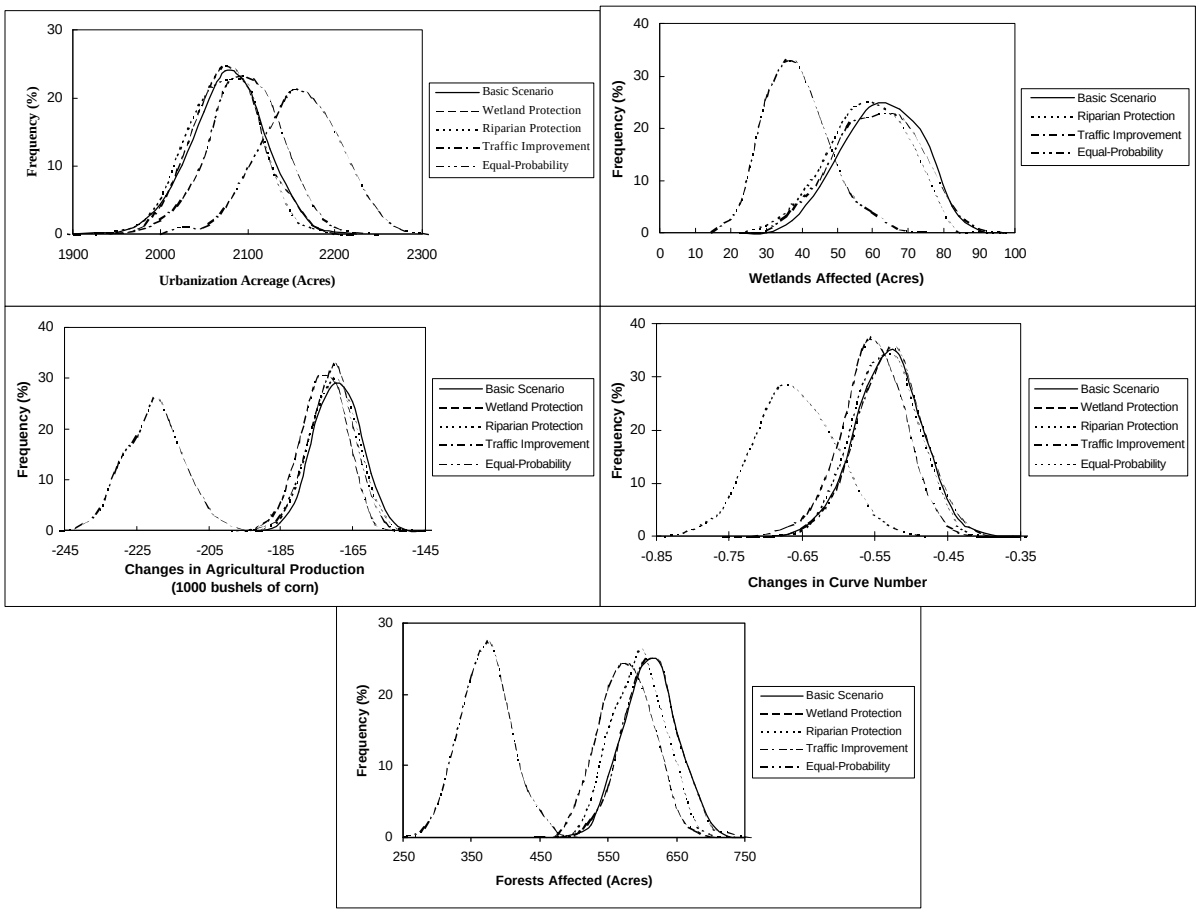

Figure 4.—Comparison of urbanization impacts from the different land use scenarios.

There are always tradeoffs between human needs and ecological or environmental protections. Since different land use patterns may result in different land use impacts, human impacts can be minimized by selection of a “ideal” land use pattern. In reality, the ideal land use pattern probably will not be automatically achieved because land use impacts are seldom included in landowners’ land use decision. However, a better understanding of land use dynamics can provide insights into the search for sustainable development and sustainable ecosystems. While actual land use patterns do not always agree with the expectation of land use planning, land use regulations and provision of public services do affect land use patterns and land use impacts. A better understanding of the mechanisms of land use change are needed to properly design public regulations and / or services that will achieve public goals.

This study presented a land use choice model and a simulation framework that can be used to interconnect human land use activities and environmental impact assessments. Land use change can be explained as a social process in which landowners make land use decisions based on their preferences. Therefore, land use choice models, which explain land use choices based on landowners' utility maximizing behaviors, are appropriate for modeling land use change in human-dominated landscapes. Social and environmental factors, as well as their interactions, can be integrated into land use choice model to explain land use patterns

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