Application of a Land Use Model for Forecasting Environmental Change*

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【Summary】

The concept of ecosystem management has become the paradigm of natural resource management. One basic principle of ecosystem management is that the social dimension and ecological dimension should be integrated together as a whole system. Environmental and ecological impacts in human-dominated landscapes are often caused by human land uses. Therefore, the interrelationships between humans and the environment need to be understood. The objective of this study is to propose a practical approach to integrating social and ecological factors in ecosystem management or environmental planning. This study uses a discrete choice model derived from observed urbanization patterns and characteristics of land and land ownership to examine the processes of land use change, and to predict future urbanization probabilities of agricultural land. The predicted urbanization probabilities are then used to simulate future urbanization patterns and their impacts on forests, wetlands, and agricultural production under different land use control scenarios. Results of the land use choice model is statistically significant, indicating that there is a relationship between urbanization of agricultural land and the observed explanatory variables. Results of the 10-yr simulations show that different land use control strategies may result in different urbanization patterns which, in turn, lead to different urbanization impacts.

Key words: land use, urbanization, discrete choice model.

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土地利用模式在預測環境變遷之應用

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摘　要

生態系經營的觀念目前已成爲自然資源經營的規範。生態系經營的一項基本原則強調生態與社會層面應該整合成於一體。而在人類活動頻繁地區，生態環境變遷多肇因於人類土地利用。因此，人類與環境間的互動關係亟待瞭解。本研究提出了一套能將社會因子與生態因子整合於生態系經營或環境規劃的實用方法。本研究依所觀察的都市擴展形態與土地及土地所有權之特性，配合離散選擇模式來預測將來各農地都市化的機率，並且據以模擬將來都市擴展的可能形態，以及土地管制措施對森林與溼地面積及農業生產的影響。土地利用選擇模式的統計結果顯示農地都市化與觀察的變數間具有顯著關係。模擬未來十年都市擴展的結果，則顯示不同土地管制措施會造成不同的都市擴展形態，對環境的影響程度也因而不盡相同。

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INTRODUCTION

Although scientific uncertainty and disputes still exist, the concept of ecosystem management has been recognized as a paradigm of natural resource management (Irland, 1994). One basic principle shared by most definitions is that ecosystem management should integrate both the human dimension and ecological dimension. For example, Salwasser (1994) indicated that ecosystem management "is about meeting human needs for livelihood while tempering human pressures on the land," and that "the success or failure of ecosystem management starts and ends with people and their choices, not with nature preserves, databases, ecological classification, or any other technological tools." The United States National Research Council, in its research agenda for conserving biological diversity, also stated that "biological diversity has been lost as a result of social processes, and will ultimately be conserved only through adjustments in these processes" (National Research Council, 1992).

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), but they have rarely gone beyond conceptual discussions (Machlis and Forester, 1996). To make conceptual models operational, a practical methodology is necessary. Therefore, the objective of this study is to propose an analytically practical approach to incorporating social factors into ecosystem management and environmental planning.

Land use systems can be interpreted as an interface reflecting the interactions between natural and social systems (Messerli and Messerli, 1978). McDonnell and Pickett (1990) also suggested that delineating ecosystem structure and function along urban-rural gradients can provide better insights into ecological phenomena as well as social-ecological interrelationships. Therefore, this study attempts to develop an empirical model for explaining land use changes by observing urbanization patterns in a rural-urban watershed. The study area is located at the fringe of a medium-sized city. The area had experienced rapid urban expansion during the past decade, and continuing urbanization may pose significant threats to the ecosystem and environment of the watershed. Specific questions addressed in this case study include: (1) What environmental and social factors might have contributed to the observed urbanization pattern in the study area? (2) How would urbanization affect environmental conditions of the study area if the trend continues? (3) How would different land use control strategies affect urbanization patterns and environmental impacts in the future?

Future urbanization patterns and their impacts under different land use scenarios are simulated and compared in this study. Urbanization impacts considered include hectares of forests and wetlands affected by urbanization, and reduction of agricultural production due to loss of farmlands.

MATERIALS AND METHODS

The study area

The study area is a watershed adjacent to the western boundary of West Lafayette in Tippecanoe County, Indiana, USA (Fig. 1). The watershed covers 72

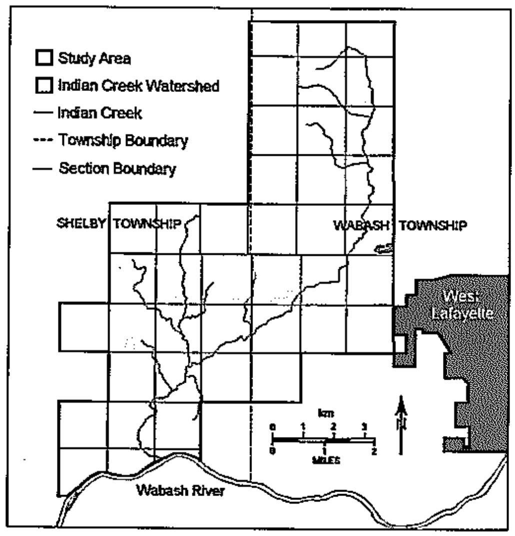

Fig. 1. Indian Creek watershed and study area near West Lafayette, Indiana, USA.

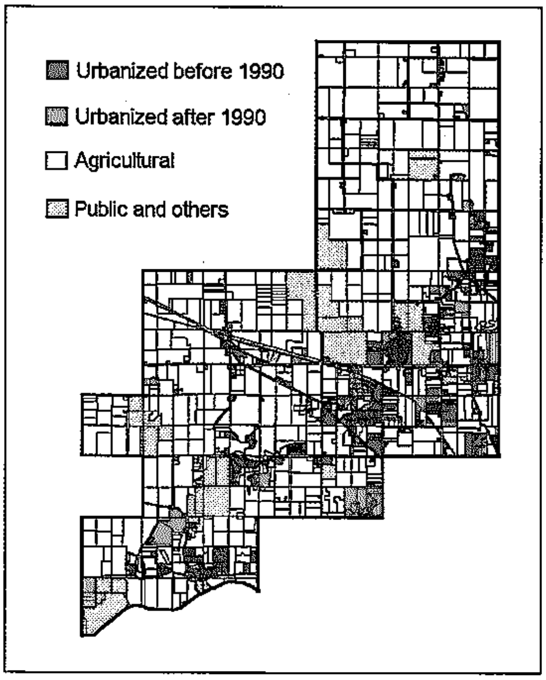

Fig. 2. Land use composition of the study area in 1995.

km^2, and Indian Creek flows 16 km from north to south into the Wabash River. To be consistent with property boundaries, the study area was delineated by 41 public land survey sections encompassing the watershed. Land uses in the study area were classified into 3 categories: (1) agricultural, (2) urban, and (3) public and others. Fig. 2 shows the land use composition and land use changes in the study area from 1989 to 1995. Agriculture has been the dominant land use, but urban influence is spreading westward from the city of West Lafayette. Urban developments were mainly residential; industrial and commercial developments were very minor. The category "public and others" includes areas designated for public services such as parks, golf courses, utilities, and cemeteries. It also includes 833 ha of land held by Purdue University.

Data collection

Data collected for the empirical analysis came from the following sources: (1) the geographical information system (GIS) database maintained by Purdue Indian Pine Natural Resources Field Station, (2) property records of Tippe canoe County, and (3) soil survey data of Tippecanoe County from the Natural Resource Conservation Service.

The GIS database maintained by Purdue Indian Pine Natural Resources Field Station contains raster-based digital maps including land ownership, road systems, and many other spatial data. Land parcels within the study area 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 to 1995. Subsequently, 631 agricultural land parcels were identified as present in 1989. Among these, 250 parcels were randomly selected to collect more detailed information. Potential factors affecting land use change were identified from literature reviews (e.g., Chapin and Weiss, 1962; Lee, 1979; Nelson, 1985; Barnard and Butcher, 1989; Knaap and Nelson, 1992). Table 1 lists the factors analyzed in this case study. Characteristics of land ownership including parcel size, frequency of land transfer, existence of land improvement, address of the landowner, and zoning regulations 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 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 sewersystems were derived from the GIS database. As a result, data for the 250 parcels at 6 different observing times were established. The land use data and the observed variables of the 1500 observations (250 parcels by 6 yr) were subsequently used to examine the relationship between urbanization decisions and the characteristics of land and land ownership.

Analytical framework

The analytical procedures of this study included 3 major steps. The 1st step was to apply a model for explaining the observed urbanization pattern and predicting future urbanization probabilities for agricultural land. Based on economic land rent theory, Brook (1987) suggested the use of discrete choice models for explaining land use decisions. The method has been successfully applied to many studies for explaining landscape patterns (e.g., Dale *et al.*, 1993) or land use change (e.g., McMillen, 1989). The land use choice model used in this study assumes that landowners make land use decisions by maximizing their utility 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 landowner *i* derived from agricultural uses and urban uses can be respectively specified as

$$U_{ai} = V_{ai} + \varepsilon_{ai}$$

and

$$U_{ui} = V_{ui} + \varepsilon_{ui},$$

where V_{ai} and V_{ui} are the systematic components of the utilities, and ε_{ai} and ε_{ai} are the random components or disturbances of the utilities. V_{ai} and V_{ui} are assumed to be dependent on a set of observed variables. Under such a specification, the probability that landowner *i* would choose to convert the land to urban uses is

$$\begin{aligned} P_i(u) &= \Pr(U_{ui} \geq U_{ai}) \\ &= \Pr(V_{ui} + \varepsilon_{ui} \geq V_{ai} + \varepsilon_{ai}) \\ &= \Pr(\varepsilon_{ai} - \varepsilon_{ui} \leq V_{ai} - V_{ui}) \end{aligned}$$

The binary logit model arises from the assumption that $\varepsilon_{ai} - \varepsilon_{ui}$ is logistically distributed. Logit models are widely used in modeling discrete choice because logistic distribution approximates the normal distribution quite well, and is analytically more convenient (Ben-Akiva and Lerman, 1985). Under this assumption, the urbanization probability for land parcel *i* is

$$P_i(u) = \frac{\exp(V_{ui})}{\exp(V_{ui}) + \exp(V_{ai})}$$

The 2nd step of the case study was to project urban growth in the study area for the next 10 yr. Housing growths in West Lafayette and its fringe areas from1989to 1995 were fitted with regression-based growth projection

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 ft (305m) 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 bounday (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)

models to estimate the growth rate. The growth rate was used to project future urban development in the region and in the study area.

The 3rd step of the study was to distribute the projected urban growth spatially and temporally to the study area. The estimated binary logit model was used to predict the urbanization probabilities of the remainingagricultural parcels in the study area. Sequences of computer-generated random numbers were used to pick parcels to be urbanized based on relative urbanization probabilities of the parcels such that parcels with higher probabilities were more likely to be selected. During the simulation, the predicted probabilities were also updated annually to reflect changes in some of the explanatory variables. The simulation process was repeated 1000 times, and each time a different sequence of random numbers was applied, so that the distributions of simulation results could be obtained.

Urbanization impacts including hectares of forests and wetlands affected by urbanization, and changes in annual agricultural production were associated with the simulated urbanization patterns. Forests and wetlands affected by urbanization were derived from the simulated urbanization patterns and maps of existing forests and wetlands (Fig. 3). Changes in agricultural production were derived from soil productivity and size of urbanized croplands.

To compare urbanization impacts under different situations, 4 land use scenarios were compared: (1) the basic scenario, which simulates urbanization patterns under existing condition; (2) the wetland-protection scenario, which prohibits urban development on wetlands; (3) the riparian-protection scenario, which sets aside riparian buffer zones to protect streams and riparian areas; and (4) the traffic-improvement scenario, which assumes that some traffic improvements were made in the southern part of the watershed. Prohibition of urban development on wetlands serves to protect the remaining wetlands. The restriction would limit the area allowable for development in parcels containing

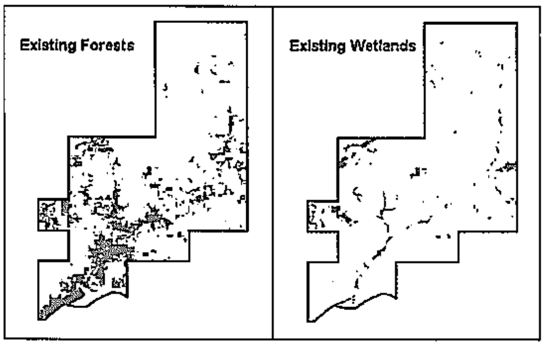

Fig. 3. Existing forests and wetlands in the study area.

wetlands,and thus may affect urbanization patterns. Delineation of buffer zones (30 m on both sides of streams) also limits the developable size of some parcels. The traffic-improvement scenario was expected to change the traffic time for parcels located at the southern part of the study area. Change of traffic time is expected to affect the urbanization probabilities and hence the urbanization patterns.

RESULTS AND DISCUSSION

The binary logit land use model

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 example, smaller parcels were found more likely to be urbanized, but the effect was less obvious as the size of a parcel became larger. Other variables such as the acreage of woodland in a parcel, percentage urbanized in a section or quarter section, and number of land transfers also showed diminishing influences. For those variables, square-root or logarithmic 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 (RFOR), and between

Table 2. Estimation results of land use choice models

Variables	Parameter estimates	Asymptotic *t*-statistics
Constant	-10.478	-2.493
TIME	-0.1866	-3.254
BLDG	1.9405	4.960
IMPROV	0.4467	2.050
SQRT(FOR)	0.3907	4.620
SQRT(SEC)	-0.4141	-3.768
SQRT(QTR)	0.3626	5.387
DWELL	0.6294	2.420
ZONING	-0.5804	-2.219
ℓn (ACRE)	-0.9164	-6.069
SQRT(TRANS)	1.3709	6.595
ADDR	1.1819	2.985
Number of observations	1500 (250 by 6 periods)	
Likelihood Ratio Test Statistic	329.133	

zoning (ZONING) and sewer accessibility (SEWER), respectively. Inclusion of such highly correlated variables would result in imprecise coefficient estimates (high standard errors) and intuitively "wrong" signs on variables. Therefore, 3 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 are shown in Table 2. Measures of the goodness of fit indicate that the model fits 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 0, suggesting that there is a relationship between the urbanization probability of a parcel and the explanatory variables.

The effects of explanatory variables in general agree with *a priori* expectations. 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 was offset by section effect. That is, as a whole section became more densely developed, the remaining agriculturalparcels became less likely to be urbanized. 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.

Fig. 4 shows the predicted urbanization probabilities of the existing agricultural parcels in 1996. Most of the parcels have low urbanization probabilities because only a few agricultural land parcels would be urbanized each year. However, the relative magnitudes of probabilities reflect that some parcels are more likely to be urbanized than others.

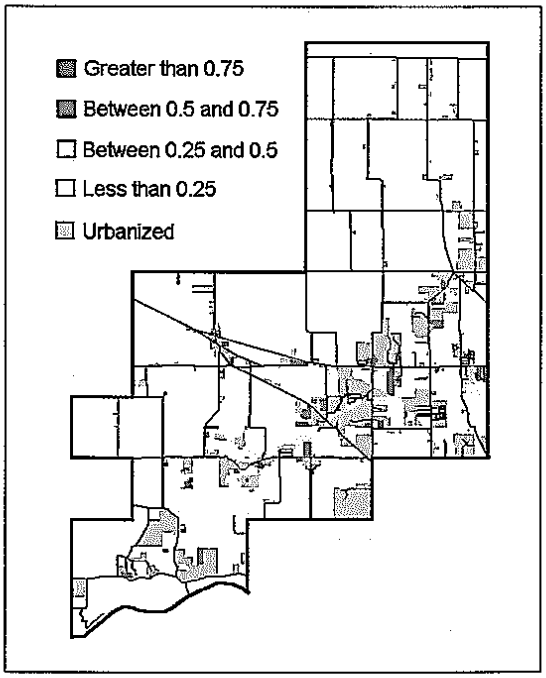

Fig. 4. Predicted urbanization probabilities of existing agricultural parcels in 1996.

Table 3. Projected regional 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

Projection of future urban development

Historical housing development in West Lafayette and its fringe area shows a linear growth trend. Therefore, future urban development in the region was extrapolated using an arithmetic regression growth model with an estimated annual growth rate of 1.745%. Housing development in the study area was projected using a ratio-based technique which predicts urban development in the study area as a proportion of the urban development in West Lafayette and its fringe areas. Table 3 shows the 10-yr projections of urban growth in West Lafayette and its fringe areas, and in the study area.

Simulated urbanization patterns and environmental impacts

Fig. 5 shows the average simulated urbanization pattern in the year 2005 according to the basic scenario. The simulated urban development is not evenly distributed across the landscape because different parcels have different urbanization probabilities. Among the 41 sections, 17 have an urbanization area greater than 20 ha. The total urbanization area within these 17 sections exceeds 70 % of the overall urbanization area.

Based on the simulated urbanization patterns, urbanization impacts under each scenario were.

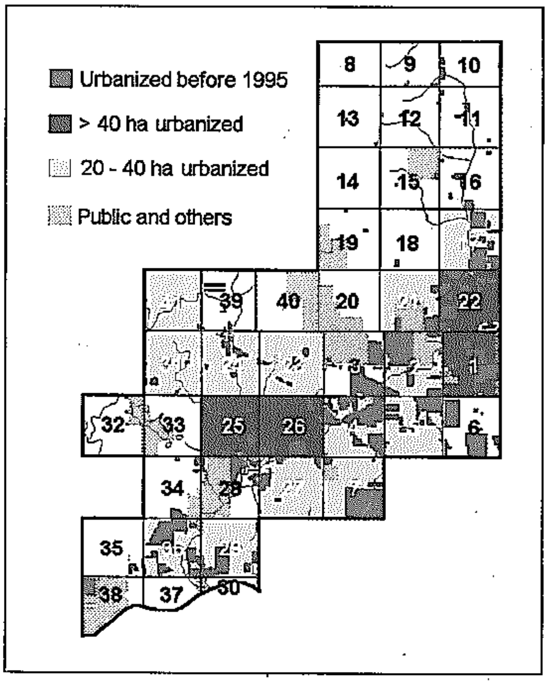

Fig. 5. Average simulated urbanization hectares under the basic scenario.

evaluated Fig. 6 compares the distributions of urbanization impacts under different land use scenarios. According to the simulated results, protecting wetlands from urban development would significantly reduce urbanization impacts on forests and wetlands, 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 area, slightly decrease impacts on wetlands, slightly increase agricultural losses, but would not significantly affect impacts on forests. Forests affected by urbanization in the basic scenario and traffic improvement scenario are quite similar in terms of size. However, they have very different spatial patterns.

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;rather, they are collectively determined by the land use preferences of individual landowners. Both environmental factors (e.g., characteristics of land) and socioeconomic factors (e.g.,

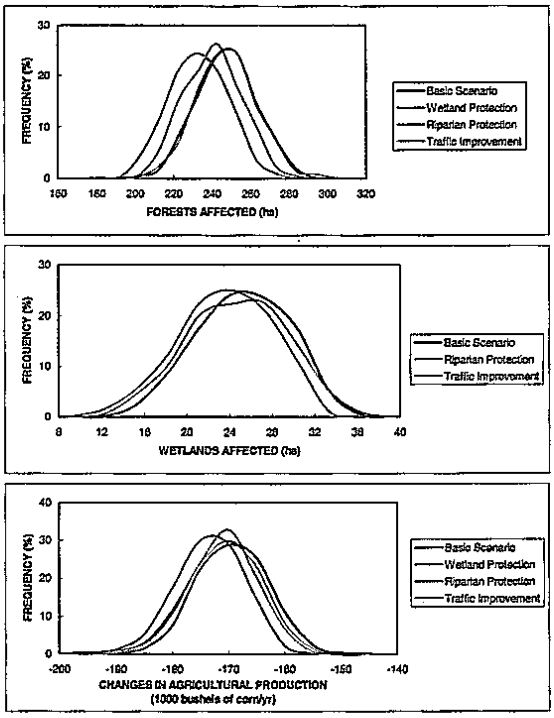

Fig. 6. Comparison of urbanization impacts between of different land use scenarios.

land use regulations, development trends, and characteristics associated with landowners) would affect landowners' land use decisions and hence land use patterns. Therefore, using discrete choice models to examine land use choices based on landowners' utility maximization behavior is appropriate. Moreover, environmental and social factors can be integrated together in discrete choice models to explain the processes of land use change.

Second, 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 obtained using repeated simulations. The simulation approach 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.

Finally, because different land areas may have different land characteristics, different spatial land use patterns may lead to different environmental impacts even at the same level of aggregate land use change. Since spatial land use patterns can be affected by land use management strategies, it follows that human impacts can be minimized if a proper land use pattern can be attained. That is, although conflicts between development and environmental impacts are inevitable, understanding the processes of land use change can provide insights for achieving balances between sustainable development and sustainable ecosystems.

LITERATURE CITED

Barnard, C. H., and W. R. Butcher. 1989. Landowner characteristics: a basis for locational decisions in the urban fringe. Am. J. Agric. Econom. 71: 679-684.

Ben-Akiva M., and S. R. Lerman. 1985. Discrete choice analysis: theory and application to travel demand. MIT Press, Cambridge, MA, USA. 390 pp.

Brooks, D. H. 1987. Land use in economic theory: principles and prospects. UDSA Econom. Res. Service, Staff Report No. AGE 870806. 16 pp.

Chapin, F. S., and S. F. Weiss. 1962. Factors influencing land development. Inst. for Res. in Soc. Sci., Univ. of North Carolina, Chapel Hill, NC, USA. 101 pp.

Dale, V. H., R. V. O'Nell, M. Pedlowski, and F. Southworth. 1993. Causes and effects of land-use change in central Rondônia, Brazil. Photogrammetric Engineering & Remote Sensing 59(6): 997-1005.

Irland, L. C. 1994. Getting from here to there: implementing ecosystem management on the ground. J. Forestry 92(8): 12-17.

Knaap, G., and A. C. Nelson. 1992. The regulated landscape: lessons on state land use planning from Oregon. Lincoln Inst. of Land Policy. Cambridge, MA, USA. 243 pp.

Lee, L. 1979. Factors affecting land use change at the urban-rural fringe. Growth and Change 10(4): 25-31.

Machlis, G. E., and D. J. Forester. 1996. The relationship between socio-economic factors and the loss of biodiversity: first efforts at theoretical and quantitative models. Pages 121-146 *in* R. C. Szaro, and D. W. Johnston, eds. Biodiversity in managed landscapes: theory and practices. Oxford Univ. Press, New York, NY, USA. 778 pp.

McDonnell, M. J., and S. T. A. Pickett. 1990. Ecosystem structure and function along urban-rural gradients: an unexploited opportunity for ecology. Ecology 71(4): 1232-1237.

McMillen, D. P. 1989. An empirical model of urban fringe land use. Land Econom. 65(2): 138-145.

Messerli, B., and P. Messerli. 1978. Wirtschaftliche Entwicklung und okologische Belastbarkeit im berggebit (MAB Schweiz). Geographica Helvetica 33:203-210. (cf. Harber, W. 1989. Using landscape ecology in planning and management. Pages 217-232 *in* I. S. Zonneveld, and R. T. T. Forman, eds. Changing landscapes: an ecological perspective. Springer-Verlag, New York, NY, USA. 286 pp.)

National Research Council (NRC). 1992. Conserving biodiversity: a research agenda for development agencies. National Academy Pr., Washington, D.C., USA. 117 pp.

Nelson, A. C. 1985. Demand, segmentation, and timing effects of an urban containment program on urban fringe land values. Urban Studies 22: 439-443.

Salwasser, H. 1994. Ecosystem management: can it sustain diversity and productivity? J. Forestry 92(8): 6-10.

Turner, B. L. II, W.B. Meyer, and D. L. Skole. 1994. Global land-use/land-cover change: Towards an integrated study. Ambio 23(1): 91-95.

Vink, A. P. A. 1983. Landscape ecology and land use. Longman Inc., New York, NY, USA. 264 pp.