PEOPLE and PIXELS

Linking Remote Sensing and Social Science

Diana Liverman, Emilio F. Moran, Ronald R. Rindfuss, and Paul C. Stern, Editors

Committee on the Human Dimensions of Global Change
Commission on Behavioral and Social Sciences and Education
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1998
Remote sensing—both data and image processing—and analysis through geographic information systems (GIS) are increasingly affecting the research agendas on global environmental change, as evidenced by various reports of the Intergovernmental Panel on Climate Change (IPCC) and the International Geosphere-Biosphere Programme (IGBP), as well as a number of initiatives by agencies and organizations that fund research on global change. The impacts of remote sensing and GIS to date have been greatest within the environmental and policy arenas because space-based and other imagery is used primarily to determine the physical attributes of the biosphere and the earth’s surface, such as forest cover or size of housing—information that is needed in spatially explicit form by various stakeholders and decision makers. The majority of the social sciences have been slow to incorporate remote sensing and GIS as basic elements of research and reluctant to respond to global-change science. The reasons are many and complex, and cannot be addressed within the scope of this chapter (see B.L. Turner, 1991, 1997a). It is sufficient to note here that the core questions of the social sciences are seen as difficult (even impossible) to address through these imaging techniques, and the understanding that might be gained in those areas from spatially explicit approaches has not been fully demonstrated or appreciated.

There are now a number of opportunities to pursue some of the core social science research issues more closely through remote sensing and GIS. Examples are issues of equity/inequity, gender, demography, institutions, democratization, (under)development, and decision making as they relate to resource use and environmental change. One such opportunity is represented by the core research project on Land-Use/Cover Change (LUCC) of the IGBP and the International
Human Dimensions Programme on Global Environmental Change (IHDP) (B.L. Turner et al., 1995). This project (or project framework) is designed to improve understanding of the human and biophysical forces that shape land-use/cover change through three means of assessment: (1) ground-based studies of use-cover dynamics, focused on the land manager; (2) space-based observation of the land-cover consequences; and (3) integrative models of these dynamics at various scales of analysis.

The objectives of the LUCC project include making remote sensing in general (but especially that involving satellite imagery) more relevant to the social, political, and economic problems and theories pertinent to land-use and land-cover change (B.L. Turner, 1997c, in press), which we euphemistically call "socializing the pixel" and "pixelizing the social." This objective involves methods and tools, such as GIS, that are relevant to analysis of spatial imagery and "gridded" data in general. Attempts to achieve this objective must invariably address issues of scalar dynamics—interpreting, merging, and analyzing the data and analysis across spatial, temporal, and hierarchical scales. These methods and tools and the associated scalar dynamics are the long-standing subjects of study and an extensive literature (e.g., Ehleringer and Field, 1993; Foody and Curran, 1994; Fox et al., 1995; Michener, 1994; Quattrochi and Goodchild, 1997; Rosswall et al., 1988; M. Turner, 1990; M. Turner et al., 1995; Woodcock and Strahler, 1987). It is not our purpose to review this work here. It is sufficient to note that the majority of this work leads up to and has significant implications for the notion of socializing and pixelizing in land-use and land-cover change research. Most of it, however, stops short of the work that is the focus of this chapter.

To date, work on the human dimensions of global change has focused largely on indirect linkages between information embedded within spatial imagery and the core themes of the social sciences. Such work is exemplified by assessments of the proximate causes of land-use and land-cover change (e.g., slash-and-burn cultivation, clear-cutting of timber), environmental constraints/opportunities associated with human activities (soil sustainability and zones of intensive cultivation), or assessments of infrastructure in planning (e.g., green spaces, road networks) (see, for example, Behrens et al., 1994; Ehrlich et al., 1997; Fischer and Nijkamp, 1993; Martin, 1996; Massart et al., 1995; Sader, 1995; Sample, 1994; Walsh et al., 1997). This work, as important as it is, tends to address factors that mediate behavioral and social actions or outcomes, and does not focus on underlying causes and structures. Exploration of more direct linkages would involve, for example, extracting information about social standing, wealth, or human health directly from the imagery (pixels), or conducting tests of a land-use theory in which such information informs the basic tenets and operation of the underlying human model.

Various efforts are now under way to advance the notions of socializing and pixelizing, although they may not employ those terms (Entwistle et al., 1997; Frohn et al., 1996; Guyer and Lambin, 1993; Wear et al., 1996). The aim of this chapter is to clarify this genre of research on land-use and land-cover change, illustrate the work through a few select examples, identify some of the scalar issues confronting research of this kind, and present some major lessons this research has begun to reveal.

**SOCIALIZING THE PIXEL**

As suggested earlier, to socialize the pixel is to take remote sensing imagery beyond its use in the applied sciences and toward its application in addressing the concerns of the social sciences. Two avenues of research of this kind offer the potential to shed light on land-use and land-cover change: mining the pixel and modeling from the pixel.

Mining the pixel involves seeking social meaning in imagery—information and indicators relevant to such concerns as economic well-being or "criticality" (Kasperson et al., 1995), perhaps signaling the underlying processes that give rise to land-use and land-cover change. This meaning is often hidden deep within the analysis of the imagery (Moran et al., 1994), and this very depth may impede such investigation. Two examples illustrate this concept.

Work in landscape ecology indicates that landscape patterns indicative of gross operating processes, some social in origin, can be identified with the use of spatially explicit indicators and fractal analysis (O'Neil et al., 1988). Might similar patterns be found through the use of remotely sensed data? Mertens and Lambin (1997) use Landsat Thematic Mapper (TM) imagery and GIS analysis to identify at least six spatial patterns of land-use and land-cover change in eastern Cameroon that are indicative of market, subsistence, policy, and urbanization processes, although the authors do not follow the pattern-process linkage fully. A rudimentary attempt to do so using TM imagery for Nepal proved difficult (Millet et al., 1995). These landscapes are a composite of rain-fed and irrigated agriculture, village forests, household trees, small grazing plots, and landslide features. Changes in the mosaics or composite patterns of these land covers appeared to signal general trajectories of the socioeconomic health and environmental sustainability of the production system at the village or village cluster level, although the sample was not sufficient to determine the statistical significance of this inference. Nevertheless, work by Moran and colleagues (1994; Mauel et al., 1993) demonstrates the details of human action that can be found in pixel analysis and, combined with the inferences from the Nepal work, suggests that further explorations of this kind are warranted.

As a second example, use of time series and principal component analyses—long used in other research—with remote sensing and GIS is gaining momentum, and this has implications for social science research (e.g., Anyamba and Eastman, 1966). For instance, a time series analysis of Advanced Very High Resolution Radiometer (AVHRR) imagery of a forest reserve in Malawi provides strong Normalized Difference Vegetation Index (NDVI)-based evidence of decreasing
forest biomass, apparently because residents adjacent to the reserve trim the trees for fuel (Eastman and Toledano, 1996). This activity, of course, has significant implications for energy consumption, human health, policy enforcement, and economic well-being. The evidence, however, is found in the seventh residual (component) of the analysis, which is usually ignored in such analyses. Nonetheless, in the study of land-use and land-cover change, the reality of the component is an empirical question because the identified human imprint can actually be observed (or not).

These two examples are surely not exhaustive of avenues of research that offer the potential to make remote sensing more relevant to social science interests. They illustrate, however, that a business-as-usual approach in the remote sensing community may not be sufficient for serving these interests. More attention must be paid to the less obvious signals in the imagery, be they complex arrays in the patterns of land cover or changes found deep within the analysis of land-use and land-cover change.

In addition to the search for social meaning in the pixel, various approaches can be used to model from the pixel toward the interests of the social sciences, although they have been minimally explored. These approaches are largely empirical and atheoretical in nature, but can be used to model land-use and land-cover change directly from remotely sensed imagery. Markov chain modeling, for example, offers a means of addressing land-use and land-cover change when the data are not spatially explicit enough or are of spatially coarse resolution. More important, however, it allows an inductive exploration of land-use and land-cover change that may provide clues about the underlying dynamics involved.

Markovian approaches assume that the immediate past is the best predictor of the near future, under the condition of stationarity, and uses transition probabilities of past states (e.g., land uses or covers or their signals in the imagery) to estimate future states. Such approaches have been used successfully for estimating change in phenomena involving processes that conform to the stationarity principle, where previous land uses are a proxy for stationary human behavior (Usher, 1981). These approaches would seem appropriate for cases involving low levels of chronic change, as in the case of subsistence-driven cultivation in forest regions that is associated with natural population growth or decline.

Unfortunately, most cases of land-use and land-cover change do not conform to the stationarity principle. Rather, changes are the result of multiple actors and structures combining in complex, synergistic ways. Moreover, critical exogenous forces, especially international and national policy decisions, may have profound effects on land-use and land-cover change. These forces can be seen as shocks to the existing land management system that fundamentally alter the pathways and trajectories of change, thus rendering the estimated probabilities from Markovian and other analyses invalid. To address some of these problems, "raw" Markov applications drawing on remotely sensed data, such as the pixel, can be socialized by accounting for various land-use and land-cover factors that change the estimated probabilities in question: soil quality or slope, management rules, resource institutions, and so on. Where this understanding can be registered to the pixel, that is, where these attributes can be recorded along with the pixel's geographic and spectral characteristics, the estimated probabilities of change from observations of the past can be altered. In this process, of course, a point is reached at which the atheoretical empirical approach is affected by the choice of the variables incorporated in the analysis, complete with their theoretical implications.

An exploration of this kind is under way as part of a Southern Yucatán Peninsula Region (SYPR) project that will produce, compare, and merge Markov modeling approaches based on remote sensing with field- and statistics-based models (see below) of the various land managers that are producing the signals registered in the imagery. SYPR focuses on the southern portions of the Mexican states of Quintana Roo and Campeche, extending along Route 186 north of the border of Petén, Guatemala. The dominant semideciduous tropical forests of the region came under assault after the highway was built, becoming the pathway for various new land users: first were slash-and-burn farmers on communally designated lands, followed by private ranchers, rice projects sponsored by non-governmental organizations (NGOs), and, more recently, various smallholder market operations and the Calakmul biosphere reserve. Virtually the entire period of major land-use and land-cover change is captured by the Landsat Multi-spectral Scanner (MSS) and TM.

A test exploiting the socialization of a Markov approach has been undertaken with MSS imagery alone as a precursor to the larger SYPR effort, and is now in its final stages. To model from the pixel as argued here, the Markovian transition probabilities of land-use and land-cover change must be made spatially explicit, and expanded through the insertion of biophysical and socioeconomic factors into the probability analysis. For the testes, three Landsat MSS images spanning the period 1975 to 1990 were used, focusing on the southern Yucatán peninsular region and more or less centered on Lago Silvite, Campeche. Six land-cover classes were derived in three land-cover maps (1975, 1986, and 1990) produced by supervised classification of MSS imagery: forest, scrub vegetation (bush and early secondary growth), natural savanna, land in crops, bare soil/roads, and water. These land-cover maps were overlaid in a GIS to create transition maps for the two periods 1975-1986 and 1986-1990. By calculating the transition probability of each cell in the land-cover maps as a function of existing land covers in the neighborhood of that cell, a spatial component was added to the transition probabilities. Multinomial logistic regressions were used to link the spatially explicit actual land-use transitions to biophysical, distance, and socioeconomic variables. A suite of models involving different combinations of explanatory variables, some of which begin to socialize each cell (pixel), were estimated for the transition types from the map for the first period (1975-1986),
and the estimated coefficients from each model were used to predict land-use changes in the following time period. These predicted probabilities of transition were then compared with actual transitions for the second period (1986-1990).

Because the basic transition during the study period was deforestation for cropland (with a minor amount for pasture), we focus here on two transitions: persistence in forest cover and conversion of forest cover to cropland. Using the spatially explicit Markov approach, the suite of models correctly predicts 94.5 to 96.5 percent of the observed persistence in forest cover for the transition period 1986-1990. This finding is not surprising given that the overwhelming land cover was forest sufficiently distant from human activity to be protected from conversion. The same suite of models was less accurate in predicting transitions from forest to cropland. In this case, the raw Markov model predicted only 16.2 percent of the observed transitions (1986-1990) correctly, but up to 20.0 percent predictive accuracy was achieved by including distance variables (to roads, villages, and markets).

These results may not seem so promising, but the conditions of the trial must be understood. First, no assessment of the classification accuracy of the identified land covers was undertaken. Second, only three social variables were used because of inadequate availability and consistency, and the surrogates used for village affluence (number of cattle and trucks) may have been inappropriate. However, most of the transition probabilities were generated for a period during which large-scale, state-sponsored agricultural projects were undertaken along the new highway, biasing transition probabilities toward high rates of forest conversion to cropland. The predicted period (1986-1990), however, witnessed a collapse of this dynamic. In short, the assumed principle of stationarity was violated.

Given this result, one might conclude that Markovian approaches of this kind may prove problematic and not useful. Yet examination of the ability of the expanded Markov models to explain the transitions found during period one (1975-1986) indicates that improvement is gained by socializing the pixel. Using the same suite of models (increasing in complexity with the addition of biophysical, distance, and socioeconomic variables), with a measure of the fit of the model increasing from 7.0 to 34.2 percent (pseudo $R^2$). This result suggests that further exploration of the socialized Markovian approach may be useful, especially with superior data and techniques accounting for time lags and shocks to land-conversion dynamics.

**PIXELIZING THE SOCIAL**

A paucity of spatially explicit data has constrained spatial modeling of human behavior and social structures, especially beyond the field of geography, and fostered modeling approaches that abstract from the essential spatial nature of the problem. As a result, either aggregate relationships are specified, or the spatial components in a model are reduced to unidimensional variables, such as the distance between economic activities in a location model, the wage differential in a migration model, or the cost of access in a transportation model. The increased availability of spatially explicit data, both remotely sensed and other data, and GIS has begun to change this situation, especially with regard to broadly interpreted land-use and land-cover change. Advances are being made in linking on-the-ground human actions and consequences to imagery (pixels) through models, or modeling to the pixel. Such efforts require, for our interests here, that each pixel (or gridded datum) be modeled to have an empirically estimated probability of change from one land use or land cover to another. In contrast to modeling from the pixel as discussed earlier, such estimates are derived by linking theoretical models directly to the imagery (Lambin, 1994), as in modeling the determinants of the decisions of individual land managers on the basis of utility maximization, satisficing, or other theories of human behavior.

Related to these approaches are questions of empirical estimation and empirical tests of hypotheses of human behavior or social structures using remotely sensed data. There appears to be a general belief among some social scientists that the uses of spatial data are restricted to enhancing the measurement and definition of explanatory variables. If this were true, the value of geographical (spatially explicit) data for the social sciences would certainly be an empirical issue and would be sensitive to the characteristics of the particular application. Better data would indeed yield higher payoffs. There are, however, additional potential gains to be realized from using spatial data. Analyzing a problem that is essentially location based without geographically coded data is analogous to analyzing a time-series problem without knowing the chronological order of the observations. The further development of statistical techniques for estimating spatially explicit models using remotely sensed data is essential, as articulated for spatial econometrics by Bockstael (1996). Taking account of the spatial nature of the problem will improve estimation and shed light on interactions and interdependencies in the system that may be interesting in their own right.

Additionally, what we euphemistically refer to as mining and modeling the pixel can be brought together in land-use and land-cover change studies. Creative explanatory variables can be constructed from remotely sensed data through the use of GIS, as with landscape patterns or land-use mosaics. If these patterns and mosaics (e.g., fragmentation, urbanization) significantly change land-management options, one could hypothesize a relationship between changing patterns in an area over time and explore the effect of that relationship on an individual land owner's current management schemes (e.g., Frohn et al., 1996). For example, using an index of the pattern as an additional explanatory variable in a model, the relationship between past and current patterns and current land-use decisions can be estimated (Geoghegan et al., 1997). However, to include such variables in an empirical specification, a model must start with a theoretical understanding of the human behavior of valuing different types of land uses and...
the distribution of those land uses across the landscape (Geoghegan and Bockstael, 1997).

Human-induced land-use and land-cover change is currently being modeled for the data-rich Patuxent Watershed of the Chesapeake Bay, revealing the spatial configuration and dynamic evolution of a landscape by capturing ecological functions, human behavior, and their interaction. The effort links remotely sensed data on land use and land cover with a variety of spatially explicit socioeconomic and physical data, as well as with separate ecological and economic models that are constructed so that the outputs of each can be easily used as inputs to the other. Each model employs a landscape perspective that captures the spatial and temporal distributions of the services and functions of the natural system and human-related phenomena, such as surrounding land-use patterns and population distributions. Configuration and reconfiguration of the landscape follows from the intertwining of these phenomena, and the Patuxent work offers the potential for a richer model of land use and its change by accounting for spatial heterogeneity and linking land-use conversion to features of the landscape. The aim is to predict the probability that a given pixel of a given description and in a given location will remain in its current use or be converted to an alternative use. While the conversion process is affected by inertia and other disequilibrium considerations and constrained by zoning and other land-use controls, the changes in land-use probabilities are functions of the value of each parcel in alternative uses. Consequently, the analysis must be able to explain what factors affect land values in alternative uses (Bockstael, 1996).

The land within the 7,000 km² of seven counties of the Patuxent Watershed located in Maryland ranges from suburbs of Washington, D.C. to rural and agricultural areas of southern Maryland. The conversion of agricultural and forested land (open use) to residential uses constitutes 78 percent of the total land-use change in these seven counties during the past 10 years. As a consequence, the economic modeling effort focuses on prediction of the conversion of open land use to residential use through a four-part process: (1) analysis of residential value as function of a variety of spatially related economic and ecological variables that are hypothesized to affect residential land values; (2) estimated on actual transactions of residential parcels; (2) use of the estimated coefficients of the expository variables from step 1 to predict values for open land of a given description were it to be converted to residential use; (3) use of these predictions with other expository variables, such as zoning, soil type, and costs of conversion, to estimate the spatial distribution of the relative probability that any such land will be developed; and (4) linking of these relative probabilities with a macroeconomic model of the state of the local economy to predict annual housing starts and thereby how much land (how many of the pixels) will change in a given year.

Many of the themes noted earlier are included in this ongoing modeling endeavor. The model is a utility-theoretic econometric model of human behavior affecting land-use decisions, not driven by GIS determinism. Using spatial data leads to interesting complications, such as spatial autocorrelation, temporal dynamics, and spatial structural change. Therefore, applying standard econometric techniques to either aggregate or disaggregate spatial data generates nonispherical disturbances, misspecification, and measurement error. New estimation techniques in spatial econometrics have been developed to take some of these issues into account in the Patuxent modeling effort (e.g., Bell and Bockstael, 1997). Whether the information gained by using spatial econometric techniques vastly improves the estimation is still an empirical issue. The initial spatial econometric modeling work with the Patuxent model demonstrates, however, the potential improvements in explaining and predicting land values (Geoghegan and Bockstael, 1995). Further improvements and refinements of both theoretical and applied econometric modeling techniques for use with the Patuxent model are presently under way.

Another theme introduced above is not just linking the pixel to people, but trying to use the remotely sensed data more creatively. For example, to better capture the spatial externalities that often characterize land use and also influence land values, indices based on the diversity and fragmentation of the surrounding landscape around each pixel have been included in the Patuxent land-value model to further explain residential land values. The intuition behind including these variables is that increasing land-use and landscape diversity may adversely affect aesthetics, but may also have convenience value signifying the proximity of important work, shopping, recreation, and institutional destinations. Which effect dominates is an empirical question. Fragmentation might be considered more obviously undesirable. Holding diversity constant, increasing fragmentation signals a hodgepodge of land uses. A high fragmentation index is synonymous with a checkered landscape, and implies the potential for large negative locational externalities. Confusion over the sign of expected effects may be very much tied to the issue of scale (see below). Preliminary estimation demonstrates that these additional GIS-created variables, measured at different scales, can add explanatory power to the Patuxent model of housing values (Geoghegan et al., 1997). Not only do these variables add explanatory power, but, depending on the scale at which they are measured, the spatial index variables of land use can be either amenities (adding to value) or disamenities (reducing value). For example, the estimated coefficient on a small-scale measure of diversity implied that individuals valued a homogenous pattern of land use in their immediate neighborhood, but the estimated coefficient of a larger-scale diversity measure implied that a higher degree of heterogeneous land uses was valued at this higher scale.

The nature and pattern of land uses surrounding a parcel have an influence on the price, implying that people care very much about the patterns of landscape around them, and supporting the belief that severe externalities exist in land use and land-use patterns.

An illustrative application of this model (Bockstael and Bell, 1997) involved steps 1-3 above (see Figure 3-1). This map shows the outcome of a model
focusing on the four southern counties of the Patuxent Watershed. Areas more darkly shaded have a higher probability of development; all non-shaded areas are land parcels that are either currently developed or precluded from development. Some of the areas of higher predicted probability of development are closer to Washington, D.C., as would be predicted by a traditional model of residential choice, whereby commuting distance is an important cost component in individuals' choices of residential location. Other areas with high probability of development are waterfront properties, as would be predicted by a simple spatial amenity model. However, it is interesting to note from this map that even after controlling for these two effects, there are still many areas dispersed throughout the region that have a high probability of development.

Given the spatially disaggregate data and GIS capabilities, hypotheses were developed to test how the distribution of land uses around a location can affect human behavior—specifically, how individuals value this distribution of land uses and how these values can affect probabilities of land-use change. The estimated econometric results on which Figure 3-1 is based suggest that individuals do value different types of land-use patterns and seek to reside in locations that have a specific distribution of local land uses, which show up as the darker areas on Figure 3-1 in regions that are not waterfront property or relatively close to Washington, D.C. Through this modeling exercise and earlier work on including spatial land-use indices in econometric models (Geoghegan et al., 1997), it was found that including disaggregate location-specific data to control for different amenities and disamenities in land use greatly enhanced the models' explained variance. Adjusting for spatial statistical issues also enhanced prediction (Bell, 1997).

SCALAR DYNAMICS AND PATH DEPENDENCE

In the Patuxent, SYPR, and other analyses, land covers are modeled as a function of biophysical and socioeconomic variables and their interactions. The critical variables change in incidence and importance, however, through time and across scales of analysis (Sanderson and Pritchard, 1993). A primary challenge in the remote sensing and GIS initiative to model these variables is to escape the tendency toward a GIS-driven determinism, which tries to account for land-cover heterogeneity through elaborate map algebra involving multiple layers of landscape features. The landscape is commonly taken to be in some kind of dynamic equilibrium: driving forces, human or not, may change, creating a kind of disturbance, but endogenous processes restore the equilibrium. Even within this framework, land use and land cover are often not a simple function of these endogenous processes; there can be time lags and spatial-diffusion processes, and the processes themselves can be buffered, amplified, inverted, or otherwise transformed before the resulting change in the landscape can be seen.

As an example, consider the case of the proposition that international agricultural prices determine a significant share of agricultural land use. To what

---

**FIGURE 3-1** Predicted probability of development: Anne Arundel, Calvert, Charles, and Prince George's counties, Maryland.
extent (and through what mechanisms) do these prices pass through to the microlevel? Is it true that all hierarchical systems conduct price signals with identical "resistance"? If not, what are the implications for using international prices as a driving force at the unit of production (land-use manager) scale? Most important, what makes different land-use systems more or less permeable to such macro-scale signals? How do these land-use system vulnerabilities vary through time?

As another example, many researchers have found strong links between the external sector (international commodity prices and exchange rate dynamics, or El Niño/Southern Oscillation [ENSO] phenomena) and changes in land use or land cover, such as forest biomass or cropping schedules. These results are difficult if not impossible to generalize across regions and nations, however, and simple correlations tend to fall apart (for a review see B.L. Turner et al., 1995). Similarly, some research postulates a straightforward link between population levels (or rates of change) and deforested area (or deforestation rates), but such relationships typically explain no more than 50 percent of the variance in forest cover across diverse regions (Mather, 1996) and commonly disappear in place-specific analysis (Kaspere et al., 1995). When these supposed mechanisms are not understood and set in context, even statistically significant correlations may be spurious. This simple but sometimes overlooked observation is one of the major scaling issues that confronts modeling efforts.

Even when these lags and transformations are taken into account, land-use and land-cover systems do not always respond in predictable ways to predicted driving forces because land cover is a function not only of socioeconomic and biophysical variables, but also of itself. A mismatch between driving forces and the state of land cover is not necessarily an indication that the scale of analysis is wrong. Endogenous, contagious processes (e.g., fire, disease outbreak, technological change and diffusion, or frontier clearing) may well explain the breakdown in predictive capacity between scale levels. It may be important to consider the extent to which a linked land-use and land-cover system exhibits its own dynamic (even apart from driving forces). If the system is path dependent, its current state and trajectory of change depend on its history (as in Markov approaches noted above), not on current values of driving forces alone.

A path-dependent system may exhibit several properties that must be considered in land-use and land-cover change assessments (Arthur, 1989): varying predictability (unpredictability is followed by high predictability as the system is "locked in"); nonergodicity (historical events are not averaged away, and small perturbations may significantly influence long-run development); progressive inflexibility (the system is ultimately insensitive to perturbation); and potential inefficiency (the outcome is not optimal for society).

Path dependency may arise from several sources, but two primary sets of dynamics are discussed in the literature. The first, self-reinforcement, is a process of increasing returns to scale (David, 1985) or network externalities, a form of increasing returns to agglomeration (Arthur, 1995; Krugman, 1994). The geographic concentration of industries, the ascendancy of particular agricultural technologies, and the dynamics of commodity booms and busts are all explicable in these terms. Historical accident may explain as much as driving forces do. The other set of processes leading to path dependency is investment rigidities— sunk costs, infrastructure development, landuse capital such as field drains and terraces, institutional evolution—that constrain and shape future development possibilities. The two are not mutually exclusive: self-reinforcing processes build their own infrastructure, leading to irreversibility and inflexibility (at least in the short run). Path dependencies and disequilibrium in land-use change are also currently being explored as part of the larger Patuxent (Irwin, 1997) and SYPR modeling projects described above.

Recognition that historical accident is critical to land-use and land-cover analysis does not preclude modeling, projecting, or other such scientific efforts. As important as path dependence may be, it does not subsume all land dynamics. The task is to identify when and where it operates and thus the spatial, temporal, and hierarchical scales in which general dynamics operate.

Why not just choose a different scale for modeling—one that spans these historically contingent processes, or one that encompasses and subsumes location-specific heterogeneity? This strategy has, in fact, been recommended for modeling based on traditional hierarchy theory. Fine-scale unpredictable processes are seen as being filtered out at higher levels of organization, so that they appear as averages or statistical distributions, with details smoothed out or aggregated. On the other hand, broad-scale processes are so slowly changing and infrequent that they appear as constraints in a model. Such "vertical decoupling" of time dynamics allows models to be built at a small range of scales, without having to be concerned about cross-scale interactions. Scaling up and scaling down thus require nesting models together and specifying the weak linkages among them (Pattee, 1973).

However, land-use and land-cover change is not a single hierarchy of processes along a continuous space-time graph, so capturing the necessary effects and dynamics is not just a question of finding the right scale of analysis. Parallel hierarchies of geological/edaphic conditions, human land-use processes, vegetative processes, and atmospheric dynamics exist (Gallopin, 1991). Scaling up and down within each hierarchy is one matter, but linking across hierarchies may occur for processes with similar spatial scales and very different time dynamics, which makes the neat predictions from the vertically decoupled world collapse.

Even within a hierarchy, levels are not static, and mechanisms for transmitting cross-scale signals are not stable. When fine-scale processes are linked together, they may give rise to sudden changes, to radical flips between alternate stable states in systems. For example, long periods of stability in relative prices may synchronize previously heterogeneous agricultural systems across a landscape. During this period, there may be a relatively strong relationship that explains incremental change in land-use systems as a function of small changes
in relative commodity prices. But the very process of synchronization may create vulnerability to a previously unimportant variable—lightning strikes, an agricultural pest, or rainfall variability—which may have existed previously, but now has a much broader-scale effect than in the heterogeneous system. Synchronization leads to a progressive loss of resilience, defined by the size of the perturbation a system can tolerate and still recover (Holling, 1986).9

Such surprises occur over multiple scale ranges, so predicting when the models will break down is as necessary as predicting change at particular scales. By exploring the interactions between slow variables (e.g., the gradual synchronization of agricultural systems in a market) and fast variables (e.g., pest outbreaks, fires), understanding can be directed toward the limits to predictability and the generation of surprise (Sanderson and Holling, 1996).

CONCLUSION

The evolution of global environmental change to global sustainability (B.L. Turner, 1997a) has enlarged the human dimensions of the research agenda, increasingly necessitating cooperation and collaboration among the natural, social, and remote sensing/GIS sciences. The LUCC project and initiatives within the project that involve socializing the pixel and pixelizing the social offer the potential to achieve such integration. They do so because they do not regard the social sciences as an appendage to the natural and remote sensing/GIS sciences, but hold the promise of providing information and understanding that speak to the core issue of social science understanding.

While largely in its infancy, work of this kind provides some rudimentary lessons that warrant special attention for the various collaborative research initiatives under way:

- Indicators of social or human-environment conditions in remotely sensed data, especially satellite imagery, are likely to be found in complex and composite patterns, requiring analytical techniques and tools to register. Since these patterns are generated by the unfolding of many processes in place, as in the Nepalese case, they are likely to be applicable only at the regional level.
- Depending on the signal in question, as the Malawi case suggests, the role of seasons and climatic flux may mask the human imprint. Analytical means must be employed to filter through the layers of information in the signal to find the human imprint of spatial processes.
- Probability approaches from the pixel per se can be made spatially explicit to meet the needs of the land-use and land-cover change research community.
- Markov chain and other such probability approaches have not been sufficiently explored in the sense of socializing the pixel, and the conditions under which they may provide robust modeling outcomes (or not) remain unclear.

ACKNOWLEDGMENTS

This paper explicates various themes under development by the International Geosphere-Biosphere Programme (IGBP)-International Human Dimensions Programme on Global Environmental Change (HDP) core project on Land-Use/Cover Change (LUCC), although it is not a formal LUCC document. Sanderson and Turner serve on the Science Steering Committee (SSC) LUCC, and Sanderson and Pritchard are, respectively, the chair and science officer of the LUCC Focus 1 Research Activity. The authors thank the SSC LUCC and various colleagues at the University of Florida and University of Maryland and in the George Perkins Marsh Institute, Clark University, for their insights. Parts of this paper were supported by the Carnegie Mellon University Center for Integrated Studies (NSF-SBR 95-21914), the U.S. Man and Biosphere Program (Tropical Ecosystems Directorate, #TEDFY94-003), the U.S. Environmental Protection Agency (#CR8219525010 and #R825309-010), and the Maryland Agricultural Experiment Station (AREC-96-62).

NOTES

1 See, for example, IGBP Report 35/LHDP Report 7 (Turner et al., 1995) or the 1995 IPCC report (Houghton et al., 1995). 2 Variously articulated, these questions can concern humanity's relationship with the mystical and religious, with itself, and with nature (B.L. Turner, 1997b). With the exception of the last question, immediate links to remote sensing are not necessarily apparent. More important, however, understanding in the social sciences is embedded in human behavior and social structures, the essence of which is not readily linked to remote sensing and, until recently, not commonly conceived in terms of spatial relations (see National Research Council, 1997). 3 It is interesting to note that many advances made in spatial geography during the 1960s and 1970s, which gave way to interdisciplinary spatial statistics and analysis more generally, are likewise applicable to the stated objective (National Research Council, 1997). Unfortunately, many of the research communities now engaged in examining the human dimensions of global change are largely
unaware of lessons learned from these efforts, and the community of these spatial researchers has not synthesized these lessons in ways that make them tractable for other communities.

4 SYFR is funded by the National Aeronautics and Space Administration’s Land-Cover and Land-Use Change initiative (NASA-NAG 50040) and involves a collaboration of the George Perkins Marsh Institute (Clark University), Harvard Forest (Harvard University), and El Colegio de la Frontera Sur—Unidad Chetumal with the assistance of Carnegie Mellon University Center for Integrated Studies (NSF-SBR95-21914).

5 While geographers have long championed the significance of place and spatial relations for understanding (National Research Council, 1997), this significance is increasingly embedded within critical social postmodern approaches to understanding, and often takes the form of “context” or “contextualization.”

6 This project is funded by the U.S. Environmental Protection Agency (Cooperative Agreement #CR82 19525010), the Maryland Agricultural Experiment Station (AREG:96-62), and the EPA/NSF Decision Making and Valuation for Environmental Policy Research Initiative (EPA Grant # R825309-010), and involves a collaboration between Clark University and the University of Maryland.

7 These values are predicated on such attributes as location, distance to features in the landscape, view, and surrounding landscape amenities and neighboring land uses, where the land use is residential or another developed use. In the case of residential land values, individuals are modeled to trade off reduced commuting distance to major employment centers for lot size, as well as neighborhood and environmental amenities.

8 Anne Arundel, Prince George’s, Calver, and Charles counties.

9 Such flips or collapses in land-use and land-cover systems are the subject of research for the emerging Resilience Network of the Beijer Institute for Ecological Economics, Stockholm.

REFERENCES


Bockstael, N.E.


1997c. Socializing the pixel in LUCC. LUCC Newsletter No. 1(Febr.):10-11.


