Modeling social systems and their interaction with the environment: A view from Geography

Diana Liverman

From: Integrated regional models : Interactions between humans and their environment.
Editors Peter M. Groffman and Gene E. Likens.
1994 Chapman and Hall NY

There is a long tradition of attempts to explain the pattern and dynamics of the human use of land and resources. A range of abstractions and computer simulations derived from theory and empirical data - models in the broadest sense - have been to describe agricultural and industrial use and misuse of the environment.

This paper provides a brief review of social science system modeling as it relates to the social causes and consequences of changes in land use and environmental quality at the regional level. The goal is to explain the assumptions of some key models and their application, and to describe some of the limitations of these models and the more general modeling enterprise.

The discipline of geography provides a useful focus for the paper because it has traditionally concerned itself with relationships between humans and the environment at the regional scale and has seen many years of lively debate about the possibilities of modeling human activity (Chorley and Haggett 1967; Macmillan 1989). Land use and environmental modeling in geography has drawn from and interacted with many other disciplines such as economics and ecology, and has seen a resurgence as a result of the new interest in global change (National Research Council 1992).

The question of regions

With regard to the question of regional modeling, geographers have discussed and debated the concept of the region for many years (Gilbert 1988; Gregory 1986; Hartshorne 1939). One view is that regions are areas of essentially uniform physical or social characteristics. The classic definition of a region is to use physiographic or other "natural" features to divide the earth into relatively homogenous areas based on topographic, climatic or vegetation characteristics. In this uniform approach to regionalization boundaries are drawn where there are distinct shifts in topography, rainfall or rainfall. Uniform regions may also be based on socioeconomic characteristics. In contrast, the functional or nodal method defines regions with reference to a major city or other center of influence and interaction.

Most regionalizations are developed according to *a priori* or *deductive* criteria, in which the classification of units into regions of common characteristics is achieved through specifying levels of income, language or social conditions which are assumed to divide the earth and nations into regions. Alternative methods of regionalization use statistical procedures in an *inductive* approach to classify data from small physical or social units into regions in which common features are identified in the statistical characteristics of the units. For example, units might be clustered according to their industrial structure or demographic characteristics using a principal component analysis of census data.

Perhaps the most important lesson of the debate about regions in geography is that both the definition of regions and the regions themselves are very dynamic. There are no immutable or sharp boundaries on the earth’s surface, especially in the social realm and in many cases research on regions must take as its first major task the identification and bounding of the region to be studied. In interdisciplinary, integrated regional studies one of the challenges is to reconcile the approaches of disciplines using different data at different scales, for example those of social scientists who work with administrative data at the scale of states and nations and the environmental scientist who uses river basins or ecosystems to define the region.

In many cases it is reasonably easy to arrive at a common definition of a region because they often seem to emerge naturally from the long historical development of human interactions with landscapes. In the United States, such regions include the Great Plains, the Midwest, the Great Lakes, the Los Angeles Basin, or New England. Geographic Information Systems provide the opportunity to overlay a variety of regional maps in order to identify appropriate commonalties and boundaries for regional analysis.

Environmental or physical models of land use

One important set of models explains land use patterns and dynamics in terms of physical and biological characteristics of the environment or region. For example, there are a range of models that have been used to estimate the best or most probable use of agricultural land based on climate, soils and topography. The work of geographers such as O.E. Baker (1926), who developed a regionalization of American agriculture based primarily on physical factors, and Griffith Taylor, who identified the environmental constraints on land use and human settlement in Australia (1930), provide early descriptive examples of this approach.

Similar assumptions about environmental controls on land use emerge from a number of recent and more quantitative studies on the agricultural potential of different regions and the world as a whole. Clark (1967) used climatic data to calculate a world area of productive land of 7.7 to 10.7 billion hectares depending on how one calculates the productivity of tropical soils. He estimated that this land could support up to 49 billion people. A similar study by Revelle (1976) estimated enough land to feed 40 billion. In a detailed study Buringh (1977) superimposed climate and soil maps to identify regions of arable and grazing potential. They concluded that 24% of global land (3.2 billion hectares) had potential for crop production. Large areas of potentially arable, but currently uncultivated, land were identified in South America, Africa and Australasia.

The work of Buringh and colleagues was the basis for a major study of the food production potential of lands in the developing world (Linnemann et al. 1979). The potential production of hundreds of soil-climate regions was estimated using simple models for 16 major crops and assumed that the highest yielding crop would be planted on each unit (Harrison 1983). The study allowed for soil fertility and moisture constraints and for three levels of technological inputs (e.g. fertilizer, irrigation). The study indicated that Africa is only using 21% of its potential arable area and Latin America only 11%, but the South East Asia is nearing its land limits at 92%. If the potential food production is compared to current population levels these models suggest that a number of regions are viewed as exceeding the capability of the land to support people i.e. their carrying capacity.

Agricultural potential models that assume that technology can be used to expand production often fail to account for the availability of capital to purchase the technology (e.g. many regions are too poor), or for the ways in which negative environmental impacts of technology - such as erosion, pollution and plant breeding - can feedback and destroy the resource base of soils, water, and genetic diversity.

A parallel set of studies in ecology explain patterns of global vegetation and biomass production primarily in terms of climate (Lieth and Whittaker 1975). The major controls on the dominant species in each region are assumed to be variables such as temperature, rainfall, and soil type. Other factors such as competition or human modification are not considered.

The dynamic version of these agricultural and ecological models can be seen in the escalating number of studies which assess the possible impacts of climate change on crop yields and vegetation (Bolin et al. 1988). Adams et al. (1990) use the output of global climate models to estimate how crop yields may change in the United States as a result of global warming. Parry et al. (1988) use a similar methodology to model the impacts of both past climate variability and possible future scenarios on crop production in different regions of the world.

Emmanuel et al. (1985) have used climate model output to perturb empirical models of the relationship between climate, vegetation type, and vegetation productivity. These climate change studies tend to assume that only climate (and often only average temperature and precipitation) will change; that climate is the most important influence; and that other factors - such as soil or technology - are assumed not to alter.

Most of the models discussed above are empirically based. The simplest are regression models of the form $y = ax + b$; where y might be crop yield or biomass and x temperature. The use of more physiologically or physically based models, which simulate processes such as photosynthesis, evaporation and nutrient flow, is limited at the regional scale by the data needs and complexity of the models. Thus, the CERES model used by Adams et al. (1990) to assess climate impacts on maize and wheat yields is heavily parameterized in simulating the day to day effects of water and nutrient stress on plant growth.

These models provide an explanation of land use grounded in a tradition of geography called environmental determinism wherein the physical environment, particularly climate, is seen as the most important influence on human activity. The more extreme versions of environmental determinism are associated with the work of Ellen Churchill Semple (1911) and Ellsworth Huntington (1915) who presented physical geography as the major explanation of not only land use but levels of development, culture, and "civilization". In this framework, regions are poor because the physical environment has limited economic growth and human potential. Although there was a strong reaction against both the scientific accuracy and political implications of environmental determinism (Peet 1985) because of its oversimplification and links to racism and imperialism, environmental explanations of land use patterns and dynamics are still prevalent, and, many would argue, relevant.

Environmental explanations of land use and land use change might also include models which treat humans as a purely biological organism whose demography responds to and has impact on the environment. Influenced by the views of Darwin, Thomas Malthus developed a model of the relationship between agricultural production and human population growth, which predicted famine as a rapidly growing population, outgrew a fixed or slowly growing food supply.

The Malthusian model has become important in many recent discussions of land use and degradation, where the intensification of land use and associated problems of erosion, deforestation and pollution are associated with rapid population growth. The work of biologists Paul Ehrlich and Garrett Hardin is characteristic in linking agricultural production and population through the concept of carrying capacity - the ability of the land to support a population based on physical resources, average per capita food needs, and population size (Ehrlich and Ehrlich 1990; Hardin 1972). If the population exceeds carrying capacity, the model suggests that hunger, environmental degradation and the destruction of biodiversity will ensue. This model also explains the rapid conversion of natural ecosystems to agricultural land to feed a voracious and fast breeding, dominant human organism at the top of the food chain.

Economic and social explanations of land use

A different approach to modeling is based in economic explanations of land use. The classic model is that developed by Von Thunen (1826) which attempts to explain the agricultural use of land on a uniform plain around a single, isolated, market. In Von Thunen's model, land uses are determined by the cost of transport to market, which depends on the distance to market and the bulk and perishability of commodities. The value of each crop to farmers (i.e. the surplus profit after production and transport costs have been paid - also called the economic rent) declines with distance from the market such that bulky or perishable products in high demand are produced close to the market, and durable, less profitable products are produced further away. This results in concentric zones of agricultural land use around a city. In Von Thunen's time, dairy and vegetables were grown in the closest ring, then the wood needed for fuel and construction, and then grains in a series of zones based on crop rotations (Figure 1).

Scholars have relaxed the assumptions of the simple Von Thunen model, allowing for variations in environmental conditions, transport infrastructure and technology, or number of markets. The modified model has been used to explain land use patterns in places as varied as Uruguay (Griffin 1973), Brazil (Waubel 1858), and the Northeast United States.

Similar economic assumptions about transport costs and markets also emerge in the industrial location models of Weber and Losch, and the settlement pattern model of Christaller (Haggett 1975; Chisholm 1962). Weber assumed that industry will locate so as to minimise costs of labor and raw material transport and to take advantage of industrial clusters or agglomerations. Losch focused on access to markets and the minimization of costs. Christaller described a theoretical model of settlement in which a hierarchy of central places providing services develops in polygonal patterns on a uniform plain. The most important assumptions of these economic land use models include those of cost (especially transport) minimization and profit maximization in free markets with rational, optimizing producers with complete and instananeous information about prices and costs. These models are typically associated with the neoclassical tradition in economics.

One major criticism of such models focuses on their assumptions of optimum behavior and perfect information. Geographers and other social scientists have developed behavioral models that assume less rational use of land, taking into account factors such as culture, inaccurate information, and suboptimal behavior. Wolpert's study of farm decision making in Middle Sweden assumed that farmers decisions about land use were constrained by factors such as information, cultural and educational background, and that decisions would be "satisficing" rather than optimum (1964). The availability of information could be simulated using diffusion models of the flow of information and technology, taking into account the influence of space, and physical and cultural communication barriers (Hagerstrand 1968). Those furthest from centers of innovation receive information later and may use the land in more traditional ways.

Diffusion models have also been applied to the widespread transformations in land use associated with the Green Revolution that brought the technologies of plant breeding and chemicals to agriculture in the Third World (Yapa 1977.)

This type of land use model often uses probabilistic Monte Carlo type methods to illustrate some the uncertainty and process in human decisions. Agricultural and other economists have also developed much more complex models of land use and environmental impacts in which some but not all of the neoclassical assumptions are relaxed. For example, linear programming models permit the optimization of locational and transport decisions based on a range of economic and physical constraints.

A more descriptive approach to land use decisions is associated with the cultural ecology of Carl Sauer that focused on the ways in which different cultures adapt to, and transform their environment (Denevan 1966). Cultural ecologists have documented the variety of ways in which traditional peoples adapted to constraints of climate and terrain through terracing, raised fields and irrigation and thus transformed severe landscapes such as the Andes and Amazon forest to agricultural land (Browder 1989).

Another view comes from political economy. In this case, the human use of land is constrained not by personal characteristics or information diffusion but by structures of economic and political power. Thus the agricultural history and geography of the United States is explained less by environment and the free market economy and more by factors such as cheap labor (e.g. slavery and the exploitation of farmworkers), the concentration of land and speculation in its value, and the intervention of government in the interest of certain powerful lobbies such as the railroad barons and agribusiness (Goodman and Redclift 1991; Fitzsimmons 1987). Third World land use and environmental degradation is explained through the legacy of colonialism in export oriented economies and land concentration, and the unequal participation of regions in the international economy (Myrdal 1957; Smith 1984).

Integrated models

The sharp distinction between environmental and socio-economic models of land use is blurred in many studies as authors relax the assumptions of their models. Incorporating variations in soil fertility in the Von Thunen model, or technology in potential production studies provides more accurate reproduction of actual land use patterns. For example a basic geography text by Kolars and Nystuen (1974) shows how the land use of the United States can be replicated in a modified Von Thunen model (Figure 2).

One set of integrated approaches are empirical models based on statistical relationships. In many cases these models include both environmental and economic explanatory variables to estimate crop yield, crop area, or measures of environmental degradation. The Universal Soil Loss Equation, frequently used to assess soil erosion potential uses both environmental (slope, rainfall) and social (farm practices) variables (Larson 1983). The degree to which variables are preselected based on theoretical grounds for use in the models varies. Allen and Barnes (1985) use a large number of variables in their attempt to estimate deforestation rates in developing countries including population growth, income, export and land use measures. Such correlation and regression models select variables on statistical rather than theoretical criteria. Econometric and linear programming models such as those of Leontiev (1977) and Heady (1964) relate land use and agricultural production to changes in input availability and demand. In these models, environmental conditions may act to influence input needs for fertilizer and irrigation, or as constraints on land expansion.

Recent development in environmental economics also link economic and environmental variables in the integration of environmental values into input-output models and cost-benefit analyses. Those models of regional economies that link production changes to both economic and environmental impacts are particularly useful in regional economic modeling.

The most complex and ambitious integrated models of the human-environment relation are world simulation models of which the best known is the World 3 model used by Meadows et al. in the book Limits to Growth (1972). This model, which treated the world as one region, projected rapid increases in arable land use until about 2020 when costs, urbanization, and erosion begin to reduce the amount of land in production. Figure 3 shows how one world model - the International Futures Simulation - structures the links between 4 sectors and 10 regions and responds to land resource constraints and government policy. IFS has been used to assess the possible impacts of global climate change on the world food system through changes in crop yields and area (Liverman 1989).

The limitations of modeling

The modeling enterprise in geography and social science has been subject to a range of criticisms. From a technical standpoint, models have been criticized as too simplistic, too aggregate, oversensitive or unable to reproduce real world conditions (Cole et al. 1973; Liverman 1989). More fundamentally, human geography and social science have evolved substantive ideological and epistemological condemnations of the formal, especially quantitative, approach to explaining society. In geography, the reaction against modeling and quantitative social science was mainly from those with humanistic and political economy perspectives (Johnston 1979;

Pepper 1986). Humanists objected to the generalizations regarding individual behavior and the quantification of intangible values in economic models. Political economists felt that the models did not capture the power relations in the political economic structure, ignored the role of the state, and were themselves a tool of elite, technocratic managers (Deutsch 1977; Cole 1973). Recent objections to the modeling of nature-society relations include those of the deep ecologists who object to the anthropocentric separation nature and society; realists who suggest that models are abstractions and cannot reproduce or forecast particular contigent conditions; feminists who see models as patriarchal or inattentive to the particular conditions of women; and postmodernists who argue that there are many different interpretations and meanings of any one phenonemon.

These multiple criticisms mean that social scientists have become rather self-conscious and self critical in attempts to model society and human-environment interactions. Colleagues may view quantitative modeling as technically impossible, socially meaningless, or even politically dangerous.

On the other hand, in a world where regions and economic sectors are increasingly interdependent, or where the understanding of environmental relations becomes ever more detailed, models offer us the possibility of managing large amounts of complex information and relationships. They force us to specify very explicitly what we know and do not know in a form that should, in some ways, be very transparent (if the model is well documented) and can thus be evaluated and modified by others, even if they speak a different language. Simulation models offer the possibility of formalizing assumptions, organizing relevant data, and specifying links and feedbacks between different economic sectors and geographical regions. The collection of data for constructing and validating a model can reveal inadequacies in the empirical evidence about environment and land use, and in a similar way, the process of constructing equations to describe the system can show where theory is inadequate. Finally, models allow us to undertake experiments and test out policy options that would be impossible or ethically unacceptable as untested experiments in the real world.

References

Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen, Jr. 1990. Global climate change and US agriculture. Nature 345(6272):219-224.

Allen J.C. amd Barnes D.F. 1985. The causes of deforestation in developing countries. Annals of the Association of American Geographers. 75:163-184.

Baker O.E. 1926. Agricultural regions of North America. Economic Geography 2:459-493.

Barney, G.O. (1980). The Global 2000 report. New York: Pergamon.

Browder J. ed. 1989. The Fragile Lands of Latin America Westview.

Buringh P. 1977. Food production potential of world. World Development. 5:477-485.

Chisholm M. 1962. Rural Settlement and Land Use.

Chorley R.J. and Haggett P. eds. 1967. Models in Geography. Methuen 816p.

Clark C. 1967. Population growth and land use New York: St. Martins.

Clark J. and S.Cole. 1975. Global Simulation models: A comparative study. London: Wiley.

Cole, H.S.D., C. Freeman, M. Jahoda, and R.L.R. Pavitt. eds. 1973. Models of Doom. New York : Universe Books.

Deutsch, K.W., B. Fitch, H. Jaguaribe, and A. Markovitz eds. 1977. Problems of World Modeling. Cambridge, MA: Ballinger.

Ehrlich P. and Ehrlich A. 1990. The Population Explosion. Simon & Schuster.

Emmanuel W.R. et al. 1985. Climate change and the broad scale distribution of terrestrial ecosystem complexes. Climatic Change 7:29-43.

FitzSimmons, Margaret I. 1987. "The New Industrial Agriculture." Economic Geography. 62(4):334-353.

Goodman D. and Redclift M. 1991. Refashioning Nature. Routledge.

Griffin E. 1973. Testing the Von Thunen theory in Uruguay. Geographical Review 63(4):500-516.

Hagerstrand T. 1968. Innovation diffusion as a spatial process. Chicago.

Hagerstrand T. 1952. The propagation of innovation waves. Lund studies in Geography. Series B. Human Geography 4:3-9.

Haggett, P. 1965. Locational Analysis in Human Geography.

Hardin, Garrett. 1972. Exploring New Ethics for Survival: The Voyage of Spaceship Beagle. New York: Viking.

Harrison, Paul. 1983. "Land and People, the Growing Pressure", in FAO Economic and Social Development Series, Land, Food and People. FAO, Rome.

Harvey D. 1966. Theoretical concepts and the analysis of agricultural land use patterns in geography. Annals of the Assocation of American Geographers. 56:361-374.

Heady E.O. amd Egbert A.C. 1964. Regional programming of efficient agricultural production patterns. Econometrica 32(3):374-386.

Hughes B.B. 1981. World Modeling. Lexington: Lexington.

Huntington, Ellsworth. 1962. "The Distribution of Civilization" pp. 391-408 in Mainsprings of Civilization. Mentor Books.

Johnston R.J. 1979. Geography and Geographers. Edward Arnold.

Kolars J.F. and Nystuen J.D. 1974. Human Geography: Spatial Design in a World Society. McGraw Hill.
Larson W.E. et al. 1983. The threat of soil erosion ot long term crop production. Science 219: 458-465.

Leontief, W. A. Carter and P. Petrie. (1977). Future of the World Economy. New York: Oxford University press.

Linnemann, H., J.de Hoogh, M.A. Keyzer, and H.D.J. Van Heemst. 1979. MOIRA : Model of International relations in Agriculture. Amsterdam : North Holland.

Liverman, D.M. 1986. The response of a global food model to climate change and variation : A sensitivity analysis of IFS. Journal of Climatology 6, 355-373.

Liverman D.M. and Frohberg K. 1988. Preliminary results of climate change scenarios in the IIASA-FAP model. Unpublished report.

Liverman D.M. 1989. Evaluating Global Models. Journal of Environmental Management 29:215-235.

Losch A. 1954. The Economics of Location. Yale University Press.

Macmillan B. ed. 1989. Remodelling Geography. Basil Blackwell.

Meadows D.H., D.L. Meadows, J. Randers, and W.K. Behrens III. 1972. Limits to Growth. New York : Universe Books.

Meadows, D.H., W. Richardson, and G. Bruckman. 1983. Groping in the Dark: A History of the first decade of Global Modeling. New York : Wiley.
Mesarovic, M., and E. Pestel. 1974. Mankind at the Turning Point. New York : E. Dutton.

Myrdal G. 1957. Economic theory and underdeveloped regions. Duckworth.

National Research Council. 1992. Global Environmental Change: The Human Dimensions. National Academy of Sciences.

Office of Technology Assessment (OTA). 1982. Global models, world futures and public policy: A critique. Washington DC:OTA.

Parry, M.L. and T.R.Carter. and N.T. Konjin eds. 1988. The Impact of Climate variations on agriculture. Vol 1 and 2. Dordecht, Holland: Reidel.

Peet, R. 1985. The social origins of environmental determinism. Annals of the Association of American Geographers. 75:309-333.

Pepper, David. 1986. The Roots of Modern Environmentalism. Croom Helm.

Revelle R. 1976. The resources available for agriculture. pp. 113-125 in Scientific American FOod and Agriculture. W.H. Freeman.

Robinson, J. 1985. Global modeling and Simulation. in R.W. Kates, J. Ausubel and M. Berberain eds. Climate Impact Assessment. New York: Wiley.

Smith N. 1984. Uneven Development: Nature, Capital and the Production of Space. Blackwell.

Taylor G. 1930. Agricultural regions of Australia. Economic Geography 6:109-134.

Thomas R.W. and R.J. Huggett. 1980. Modelling in Geography. Totowa, NJ : Barnes and Noble.

Von Thunen J.H. 1875. The Isolated State.

Wolpert J. 1964. The decision process in a spatial context. Annals of the Association of American Geographer 54:537-558.

Yapa L.S. 1977. The Green Revolution : a diffusion model. Annals of the Association of American Geographers 67:350-359.