

Integrated Modeling of Land Use and Cover Change

A conceptual scheme for applying an integration strategy to agricultural land use on the US Great Plains

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Local and regional land-use and land-cover change is an important ingredient in the larger problem of global environmental change. Land-use patterns, driven by a variety of social processes, result in land-cover changes that affect biodiversity, water and radiation budgets, trace-gas emissions, and other factors that, cumulatively, alter the global climate and biosphere. Most research on global environmental change has focused on the causes and impacts of global climate change and ozone depletion, with less attention to biodiversity trends. Land-use and land-cover studies have been entrained in this work only secondarily, for example, to calculate the rate of loss of tropical forests or to assess habitat fragmentation.

Land-use and land-cover change is gaining recognition as a key driver of environmental change. The re-

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searchers studying global environmental change are calling for historical reconstructions of land use and cover, analysis of the social forces behind land transformations, and modeling approaches that can be linked to other types of environmental simulations, such as global climate models (Jacobson and Price 1991, Stern et al. 1992).

An integrated agenda for land-use/land-cover change research is emerging (Stern et al. 1992, Turner and Meyer 1991), and a new International Geosphere-Biosphere Program (IGBP) core project has been initiated to assess and model regional-to-global land-use/land-cover change (Turner et al. 1993). As in many efforts to understand complex natural or social phenomena, the emerging land-use research agenda stresses simulation modeling as a tool that integrates theoretical and empirical analysis and offers some level of prediction capability.

Efforts to model environment and society interaction appear to be taking one of two strategic routes. The

first is to build new models from the ground up, encapsulating into model design (as suggested by Robinson 1991) the currently quite limited theory on interaction between environment and society. The second route is to link existing simulation models. Our sense of existing model capabilities suggests that a hybridization of these two approaches will be most productive, with research groups linking existing models while also modifying them with new algorithms for sociocultural behavior and ecosystem responses.

At this stage in development of a land-use/land-cover component of research on global environmental change, it would be useful to think through a strategy for linking and modifying models in a way that integrates social and natural processes and translates conceptual schema into functioning simulation models. In this article, we evaluate the state of land-use studies and models, offer a conceptual schematic for integrated analysis, and suggest ways to implement the conceptual models using existing simulation models. We provide a regional context to this integration strategy by drawing on previous research into agricultural land use on the US Great Plains.

The status of land-use and land-cover studies

Unfortunately, the field of land-use studies is poorly prepared for its new role in research on global change. Like descriptive climatology, which was little more than

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score-keeping when demand for a more dynamic climatology developed in the 1970s, the study of land use is largely comprised of theoretical classification and mapping efforts. The needed transition from conventional land-use studies to a more analytical endeavor based on theory and modeling will be difficult, but it should be aided by growing attention to the role of land-surface processes in global change and by development of fields such as landscape ecology and of tools such as geographic information systems.

One way to hasten this transition is to link the theoretical aspects of land-use study with the field's descriptive and classificatory arm. Land-use has been depicted theoretically as an equilibrating process in which land value (or rent) is established by inherent characteristics (soils, climate, and slope), location (especially with regard to urban centers and transportation access), and supply and demand (Birch 1968). Economists have focused on the demand side of land value, and geographers and planners focused on location and ownership, with both groups neglecting biophysical characteristics. Behavioral, cultural, and political factors have also been neglected in land-use studies, but they are central to recent calls, as part of research on global environmental change, for elaborated studies on land-use change.

The broader driving forces behind land-use and land-cover change have been codified by two focused efforts: the Human Dimensions of Global Environmental Change program (Stern et al. 1992, Turner et al. 1993) and the University Corporation for Atmospheric Research/Office of Interdisciplinary Earth Studies Snowmass Workshop on land-use and land-cover change (Meyer and Turner in press). The roster of forces runs from the most obvious, such as population, technology, and consumption, to the more subtle, such as attitudes and values. But few studies demonstrate how such factors play out in an actual landscape. We draw on this roster in our effort to create a conceptual model of land-use change, using the US Great Plains to provide an environmental and social context.

Ecological and social systems in the Great Plains

The US Great Plains provide an excellent natural laboratory for examining the interaction of society and landscape given the solid base of existing regional ecological, agricultural, and social research that exists (Burke et al. 1991, Riebsame 1990). The Great Plains are a natural grassland covering a roughly rectangular area bounded by the prairies and forests of the Mississippi Lowlands to the east, the Rocky Mountains to the west, the boreal forests in Canada to the north, and the desert shrublands of Texas and New Mexico to the south.

The Plains have experienced significant land-use change over the last century, as the original grasslands were transformed by dryland and irrigated agriculture and livestock grazing, and as population and development ebbed and flowed with the region's economic fortunes. Today, the region is characterized by a rather simple land-use matrix: more than 90% of the region is in agricultural use, divided roughly equally between cropping and grazing, with the remainder devoted to urban and suburban use, transportation facilities, energy development, and nature preserves (Riebsame 1990).

A rich body of regional research describes how these land-use patterns have been shaped by climatic, economic, social, and policy factors (Kraenzel 1955). The dominant theme in this work has been the counterbalancing of aridity, as a limit to agricultural potential, and strong social and policy desires to create an extensive agricultural ecology and economy (Riebsame 1990, Worster 1979). Changing market forces, environmental impacts, and challenges to government subsidies for extensive cultivation of the region, however, have conspired recently to weaken the ecological and social logic of Great Plains agriculture (Popper and Popper 1987, Worster 1979). In attempting to create a conceptual model of Plains land use, we draw on two rich bodies of related work, studies on regional agroecological systems and research on social systems.

Agroecosystems. The relationships among climatic patterns, soils, and agricultural and rangeland production in the Great Plains have been extensively investigated. Over the past two decades, the relationships have been successfully modeled (e.g., Burke et al. 1989, Sala et al. 1988). Climate and soil are the dominant controls of biological productivity. Nitrogen is an important factor in grass and crop production when moisture is not limiting, and soils generally become more sandy from east to west across the Plains, thus losing their water-holding capacity.

Within this matrix of climate and soil controls, a mosaic of land uses has emerged, dominated by heavily modified grazing lands, some residual native grasslands, and dryland and irrigated croplands. The eastern fringe of the original grassland was first cultivated by indigenous populations, but it was not until after the US Civil War that large-scale human settlement occurred. People were lured to the Plains by grants of land on which they were encouraged to grow flax, small grains, and corn.

Regional agricultural patterns have been extensively described (Smika 1992). The Great Plains is the country's dominant winter and spring wheat production area (Smika 1992), with a landscape marked by extensive, uniform blocks of wheat in a matrix of grazing lands. Wheat in the western Plains is grown in a summer fallow rotation in which each parcel is idled every other year, often in alternating crop and fallow strips orthogonal to the prevailing wind. The fallowed land stores moisture, enhancing subsequent crop growth despite typical summer dryness. Less than 10% of the regional crop area is irrigated; much of the irrigation is located along major rivers or in the central Plains, where groundwater is easily tapped. Grazing lands intersperse the crop areas, becoming more extensive from east to west as crop cultivation becomes more risky due to increasing aridity.

Although most agricultural land-use data for the Plains has been arrayed by county units (and thus are not readily linked to point or small-area data for ecological variables), spatially arrayed regional

land-use and land-cover data sets are now being created. The Soil Conservation Service is creating a rich agricultural land-use and land-condition database as part of its Resource Conservation Act appraisals (USDA 1989), and Burke et al. (1991) are creating a geographic database of land use for the central Plains by linking remotely sensed data to land-use records collected for regulatory and farm support programs. These developing databases can provide the basis for spatially explicit regional modeling.

Agrosocial systems. The social elements of Plains agriculture have been the subject of a great deal of sociological, anthropological, and geographical analysis. Perhaps nowhere else in the United States has social science focused so much on why people have used the land in the way they have (Lawson and Baker 1981, Rielsame 1990).

Over the years, explanatory themes have shifted from more narrow interpretations, such as climate determinism (Webb 1931), toward analysis of environmental perception (Saarinen 1966), natural hazards (Warrick and Bowden 1981), and changing social structures (Ottozon et al. 1966). The climate determinists tended to explain land use as a simple function of the limits imposed by aridity, whereas those focusing on hazards, risks, and social structure have offered multi-causal explanations of how perceptions and institutions were adjusted as agricultural settlement proceeded from east to west across the United States toward more arid regions.

The common theoretical thread to this work has been a human-ecological model in which people and institutions are likened to organisms adapting to their environment (e.g., Bennett 1982). In his classic work on family agropastoralists in the northern Plains, Bennett (1969, 1982) described the intricate relationships between institutions (e.g., family, community, and government agency) and resource management in the Plains environment, arguing that agriculturists had adapted to environmental marginality by changing type, timing, and technology of their ac-

tivities and by manipulating the social and policy environment to meet individual and collective goals.

At the regional scale, social analysts have maintained this ecological theme by focusing on the environmental fitness of Plains social institutions (Kraenzel 1955, Ottozon et al. 1966, Worster 1979). They have paid special attention to the hypothesis that the original settlement pattern of towns, counties, and infrastructure was a case of developmental overshoot, with populations exceeding what today would be called carrying capacity. Believing that early settlement made too many people dependent on an uncertain and low-productivity environment, Plains analysts explain continuing regional out-migration as a straightforward process of downward population adjustment to meet habitat capacity.

An enlarging rural sociology literature maintains this theme, but it also looks for aspects of Plains society that are more robust and resilient (Murdock et al. 1987). Human-ecological inquiry in the Plains has been enlivened by recent debate on the overall sustainability of regional agriculture, with some observers arguing that the region is on the verge of a catastrophic social and ecological collapse because institutions have not fully adjusted to limits of the environment (Popper and Popper 1987, Worster 1979).

A conceptual model of Great Plains land use

Questions about regional land-use/land-cover change posed under the rubric of global environmental change can be illuminated by linking the broad theory of land-use to a detailed conceptual model of agricultural land use on the Great Plains. At the broadest level of abstraction (Erhlich and Erhlich 1990), the drivers of land-use change have been conceptualized as

$$I = PAT$$

where impact (or change) is a function of population (P), affluence (A), and technology (T). This formulation embodies the conventional emphasis on economic factors (e.g.,

production and consumption).

Other researchers have recognized the need to expand the notion of driving forces to encompass all realms of social life (Meyer and Turner 1992, Stern et al. 1992, Turner and Meyer 1991), especially people's aspirations, perceptions, and attitudes and features of social and political institutions, such as how land is traditionally divided within families or how the government taxes inheritance. These factors—which we label sociocultural here—had been neglected because they are difficult to quantify and to operationalize in mathematical simulation models.

Research on Great Plains agriculture suggests that a more-detailed conceptual schema for land-use modeling must have four component realms: driving forces in the human environment, driving forces in the physical environment, land-use decision processes, and ecological processes. Our attempt to create such a schema (Figure 1) includes these realms and also reflects existing modeling capabilities. We link the physical and human realms by modules representing existing models of agroecological processes and of farm and ranch management. The conceptual schema is designed not only to organize our thinking but also to provide guidance to a hybrid approach to land-use simulation modeling in which existing computer simulation models are linked and modified.

The physical-environment realm of the integrated model (Figure 1) is comprised of the traditional factors of climate, soils, and biogeochemical cycles. These factors feed into three ecological-process domains of an existing agroecosystem model: soil water dynamics, plant production processes (crop and grass growth), and soil organic matter dynamics (especially carbon fluxes).

The human environment side of the conceptual model encompasses the broad driving forces of policy (e.g., price supports and conservation programs), economy (e.g., demand, input costs, and commodity prices), and technology (e.g., production options and their likely adoption), as do other models. But, we suggest more attention to a ros-

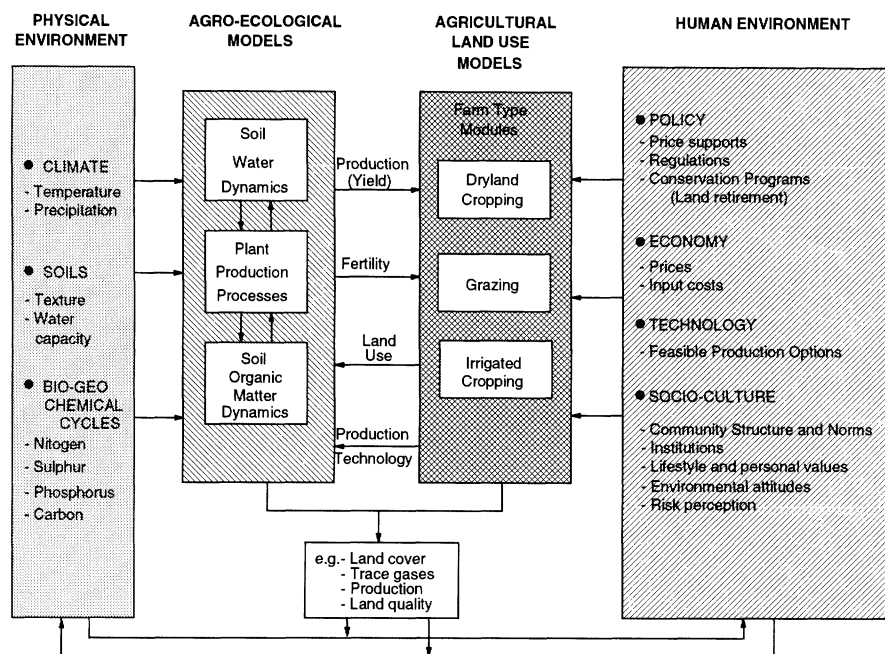


Figure 1. A conceptual model of Great Plains agricultural land use, anchored by large-scale driving forces in the physical (left) and human (right) environments and centered on land-use decisions and ecological processes encapsulated in simulation models.

ter of sociocultural factors, such as community norms and environmental attitudes and perceptions, which have been neglected in previous modeling efforts. Community norms, perceptions, and life-style choices are critical to how the driving forces are translated into goals and means at the farm or ranch level, where actual land-use choices are made.

Useful modeling of land use must also explicate the interactions and feedbacks among land use, technology choices, and ecological processes. For example, farmers choose among cultivation practices that require varying levels of soil fertility and plant production and that simultaneously affect soil fertility and other biogeochemical states. Reduced tillage practices, by retaining more crop residue than conventional approaches, can increase soil organic matter. This increased fertility and water-holding capacity, once recognized by farmers, affects choices about chemical inputs and future uses of land parcels. These feedbacks, portrayed by arrows linking the four main elements of Figure 1, must be explicitly modeled to achieve the needed integration of natural and social processes in future simulation models.

Making the conceptual model operational

Modeling skill varies across the social and ecological realms of Figure 1. Interactions among climate, water, soil, and agricultural production are fairly well understood and expressed in validated simulation models. Resource-use decision models are based on well-described economic processes, and, indeed, land use is often explained exclusively in economic terms because of the ease with which monetary values and transactions are quantified. Simulation models validated for Great Plains conditions exist for each of these processes. We describe these models and suggest how they might be modified and linked to form the base of a new, integrated land-use model.

Agroecological models. A subset of general ecological models, agroecological models are designed specifically to simulate human-dominated ecological processes under conditions of cropping and grazing. They are used to calculate biomass production, carbon flux, and other ecological aspects of natural vegetation and crop covers. For example, the

Century Agro-Ecosystem Model (developed at Colorado State University; see Paustian et al. 1992, Parton et al. 1987, 1988) simulates ecological processes for an agricultural land-use model because it integrates climate, soil, and cultivation practices. Moreover, because this model requires land use as input, it is well suited to link social and ecological processes.

The general version of Century has thus far been applied to temperate agroecosystems (Paustian et al. 1992), savanna woodlands, and temperate and tropical forest systems (Sanford et al. 1991). It simulates plant production, soil organic-matter dynamics, and nutrient (nitrogen, phosphorus, and sulfur) cycling at a monthly time scale, based on such inputs as data on precipitation, air temperature, soil texture, and land treatment.

The grassland version of Century has been tested extensively using soil carbon and nitrogen, plant production, and live biomass data from grasslands in the Great Plains and Russia (Burke et al. 1989). Comparisons of observed and simulated annual plant production at the Konza Tallgrass site in Kansas and at the Central Plains Experimental Range in eastern Colorado include burned and unburned sites and sites that have been fertilized and/or irrigated. These comparisons show that Century simulates within 25% of observed values the plant production and seasonal peaks in live biomass under the different treatments.

Century's agriculture submodel has been tested using observed data on plant production, soil carbon, and nitrogen from several long-term agricultural experimental sites. At Pendleton, Oregon, and at a site in Sweden, the model successfully simulated the impact of different types of organic matter additions on crop production and carbon and nitrogen levels in the soil (Paustian et al. 1992).

Metherell and Cole¹ have successfully used Century to simulate

¹A. Metherell and C. V. Cole, 1993, personal communication. Natural Resources Ecology Laboratory and Agricultural Research Service, USDA, Colorado State University, Fort Collins, Colorado.

the effect of different tillage practices (no-till, stubble mulch, and moldboard plow) on soil carbon and nitrogen levels and corn and wheat yields at Sidney, Nebraska, and Weld County, Colorado, based on historic management documented by Greb et al. (1979). Metherell and Cole were able to simulate the yield increases observed throughout the Great Plains since approximately 1930 and to evaluate the contributions to this trend by new tillage practices (e.g., stubble mulching), improved varieties (e.g., with increased harvest factor), and increased fertilizer application.

Finally, Century has been used to simulate the potential impact of climatic changes on soil carbon storage and plant production in the southern Great Plains (Burke et al. 1991, Schimel et al. 1991). These studies found that increased air temperature causes soil carbon and nitrogen levels to decrease, nutrient cycling rates and plant production to increase, and increased nitrogen gas fluxes (N_2 , N_2O and NO_x). The results suggest that potential losses of soil carbon and nitrogen from grasslands under global warming would be small compared with changes in soil organic-matter levels due to land-use changes, such as transforming grasslands into croplands (Burke et al. 1991).

Models of farm and ranch management. The land-use inputs necessary to an agroecological model must be calculated by simulating the choices made by farmers and ranchers in the context of market, policy, and sociocultural forces. Agricultural economists have developed models to explain and predict farmers' resource allocation decisions using two chief methods.

The econometric approach uses multiple regression to simulate response to a classic set of variables such as crop prices or land productivity. Although this method has been quite successful at simulating farm activities, it poorly captures conditions outside the range of historical observations and is thus ill-suited to analysis of response to significant environmental changes such as global warming.

The other approach, called opti-

mization modeling, attempts to mimic farmer decision making based on a priori rules. Optimization models assume that producers make profit- or utility-maximizing choices within an environment consisting of natural resource characteristics, available technologies, constraints on productive resources, input and product prices, and the constraints and incentives of government policy (see Day and Sparling 1977, Hazell and Norton 1986 for detailed historical reviews and critiques of optimization methods).

The earliest optimizing tool was the farm-budget model, which calculated net farm income for various land-use and technology mixtures. The analyst made a priori assumptions about crop species and rotation patterns, production technology, and prices of inputs and products. The simple budget approach has been supplanted by mathematical programming techniques that incorporate not only crop and technology choices (Anderson et al. 1977, Hazell and Norton 1986) but also can reflect considerations of production and price risk, tax policy, and credit within multiyear simulations (Baum and Richardson 1983, Day 1987).

Farm management models useful for integrated land-use modeling must simulate interrelated farm management choices, primarily selection of crops and rotations, and also choices of input levels and production technologies. Mathematical programming models for typical Great Plains farm and ranch types have been developed (Burt and Allison 1963, Carrande 1992, Young et al. 1982). More recently, using a method called discrete, stochastic sequential programming (Rae 1971), Young and colleagues modeled crop and technology choice and water use on lands irrigated from the Ogallala Aquifer in eastern Colorado. Their approach explicitly incorporates probabilistic outcomes and the cumulative effect of sequential decisions into the analysis by extending static, single-stage linear programming to multistage, stochastic modeling. Taylor and Young (1993) have shown that this approach, incorporating probabilities of rainfall and surface-water

supplies, can explain observed cropping patterns and irrigation decisions better than a conventional static programming model.

Modifying and linking ecological and social models

Agroecological models such as Century are naturally compatible with farm and ranch management models, inasmuch as the former need inputs about land use and technology, whereas the latter require inputs on fertility, production, and other ecological processes. Artificial fertilization is rather easily input to the agroecological model, and production can be readily input to farm management models, as suggested by arrows in Figure 1. But a remaining difficulty in this data exchange is the need to account for temporal and geographic scale differences among social and natural processes.

Our conceptual model combines changes that operate at scales ranging from the hourly and daily (e.g., water dynamics) to the decadal (e.g., land-cover change). Ways to handle these differences must be developed. It may be necessary to run multiple versions of the model in an ensemble representing different response time scales, with accounting subroutines to keep track of the changes accruing at different time frames, for example, in soil fertility, vegetation cover, or government policy, and to reintroduce these changed conditions into future runs of the model. Ability to manage geographic differences in land-use modeling awaits further integration of geographic information systems and simulation modeling (Lee et al. 1992). Although Century has been linked to a geographic information service (Burke et al. 1991), decision models have not.

Despite the complexity of multiple temporal and spatial scales, however, the greatest challenge to integrated land-use modeling lies in incorporating nonquantitative sociocultural factors to create more realistic and complete representations of farmers' decision making. Unlike knowledge of ecological and economic processes, most social science insights into how people transform their environment have not

been translated into simulation models. Sociocultural factors, such as community norms, perceptions, and personal goals, have received little attention by modelers (Day 1987).

The task of modeling sociocultural forces is difficult because humans act both as individual decision makers (as assumed in most econometric models) and as members of a social system. Sometimes these roles have conflicting goals (Etzioni 1988). A unifying hypothesis that links the ecological and social realms, and an important reason for pursuing integrated modeling, is that humans respond to cues both from the physical environment (e.g., soil erosion) and from sociocultural contexts (e.g., conservation policy) and behave to increase both economic and sociocultural well-being (Knop 1987a,b). This pattern of behavior is important to consider, because economic models tend to aggregate individual action but neglect the emergent properties of collective values and actions.

A tactical modeling decision is needed. The current land-use models typically translate economic value into choices by comparison with a priori performance criteria (goals) and limiting functions (constraints). Rather than try to create new algorithms to handle, for example, attitudinal biases or attempts to abide by ill-defined community norms, we suggest using what is known about such sociocultural forces to modify the values of the objective functions already modeled. For example, the conventional economic criteria of maximized return on investment or end-of-period net worth might be relaxed in light of studies indicating that farmer behavior is neither strictly economically or ecologically rational (Day 1987, Lovejoy and Napier 1986). Rather, a set of alternative goals have been documented, especially providing a desired level of consumption for the family, increasing chances of farm survival in bad times, enhancing the likelihood that the farm will stay in the family, meeting conservation goals often set by local custom, and abiding by community norms of farm management, especially with regard to debt and the use of family labor.

The need, of course, is to docu-

ment local and regional customs and constraints and to adjust the performance and constraint parameters of the objective models accordingly. For example, sandy soils or wetlands can be constrained from cultivation by farmers who abide by local customs of environmental conservation, even if market forces dictate their use. Or the optimization routine can be constrained from simulating changes in crop choice if community norms or government policy limit the acceptability of alternatives. Finally, requirements for positive financial return might be relaxed, given goals and strategies for staying in farming or holding onto the farm despite negative cash flow in order to pass it on to children. Such goals and means become the proximate causes of land-use change, as conceptualized by Stern et al. (1992) and Turner and Meyer (1991).

The knowledge needed to adjust objective models in this way can come only from interviews with or participant observation of farmers and ranchers, with the obvious prescription that future field studies include inquiry into custom and culture as well as resources and finances. This strategy of collecting nontraditional data from land users and using it to modify model parameters demands new research techniques. The traditional questionnaire or farm-budget analysis does not suffice, and land-use researchers need to apply the enlarged roster of qualitative tools now available (Strauss and Corbin 1990).

Assessing regional change and sustainability

Integrated land-use models are needed to assess the effects of changes in major driving factors (e.g., climate, prices, policy, and people's attitudes). Some questions about regional land-use and land-cover change in an agricultural context that could be addressed in this way are:

- How much and what kinds of land are likely to switch in and out of production under different market and policy conditions?
- What land in different ecological classes is treated with cropping and

grazing technologies that are ecologically sustainable (e.g., as measured by soil carbon balance)? Which of these land uses appear to be socially acceptable and sustainable?

- What lands are most likely to switch out of production in a worsening climate and decreased government subsidy?

An obvious application of integrated land-use models to research on the human dimensions of global environmental change is to assess regional effects of climate change under different economic and policy situations. The agroecosystems modules would be used to simulate crop yields and soil fertility associated with global warming scenarios, and these would be introduced, along with economic and policy changes, into the farm management models to drive simulated land-use adjustments. Rather than prediction *per se*, the value of such modeling efforts comes from sensitivity analyses that assess the impacts of climate change across a range of economic and policy contexts. Such simulations would begin to identify the fingerprint of potential future environmental and social change in regions such as the Great Plains, and they would provide a firmer basis for global change monitoring and policy prescriptions.

Finally, integrated land-use models could also be used to explore the notion of regional sustainability. The long-term sustainability of Great Plains agriculture is in doubt, regardless of the potential for climate change (Popper and Popper 1987, Riebsame 1991). We think that conflicting evaluations of regional development arise because sustainability has not been well defined and because analysts tend to focus on purely ecological or social factors, not their interaction. Indicators of sustainability (e.g., soil fertility and farm survival) should be calculated under different scenarios of technology, markets, and policy. Sensitivity analyses based on both traditional and innovative measures of sustainability could move researchers beyond arguments over definitions, while providing a foundation for assessing more encompassing sustainability goals such as ecosystem health and rural community well-being.

References cited

- Anderson, J. R., J. L. Dillon, and J. B. Hardaker. 1977. *Agricultural Decision Analysis*. Iowa State University Press, Ames.
- Baum, K. H., and J. W. Richardson. 1983. FLIPCOM: farm-level continuous optimization models for integrated policy analysis. Pages 121–139 in K. H. Baum and L. P. Schertz, eds. *Modeling Farm Decisions for Policy Analysis*. Westview, Boulder, CO.
- Bennett, J. W. 1969. *Northern Plainsmen: Adaptive Strategy and Agrarian Life*. AHM Publ., Arlington Heights, IL.
- _____. 1982. *Of Time and the Enterprise: North American Family Farm Management in a Context of Resource Marginality*. University of Minnesota Press, Minneapolis.
- Birch, J. W. 1968. Rural land use: a central theme in geography. Pages 13–28 in E. Embleton and C. Coppock, eds. *Land Use and Resources: Studies in Applied Geography*. Alden and Mowbray, London, UK.
- Burke, I. C., T. G. F. Kittel, W. K. Lauenroth, P. Snook, C. M. Yonker, and W. J. Parton. 1991. Regional analysis of the Central Great Plains. *BioScience* 41: 685–692.
- Burke, I. C., C. M. Yonker, W. J. Parton, C. V. Cole, K. Flach, and D. S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. *Soil Sci. Soc. Am. J.* 53: 800–805.
- Burt, O. R., and H. Allison. 1963. Farm management decisions with dynamic programming. *J. Farm Econ.* 45: 121–136.
- Carrande, V. G. 1992. Optimization of rangeland management strategies under production and market risks. Doctoral dissertation, Colorado State University, Fort Collins, CO.
- Day, R. H. 1987. Farm decisions, adaptive economics, and complex behavior in agriculture. Pages 18–49 in K. H. Baum and L. P. Schertz, eds. *Modeling Farm Decisions for Policy Analysis*. Westview, Boulder, CO.
- Day, R. H., and E. W. Sparling. 1977. Optimization models in agricultural and resource economics. Pages 35–49 in L. Martin, ed. *A Survey of Agricultural Economics Literature*. vol. 2. University of Minnesota Press, Minneapolis.
- Ehrlich, P. R., and A. H. Ehrlich. 1990. *The Population Explosion*. Simon and Shuster, New York.
- Etzioni, A. 1988. *The Moral Dimension: Toward a New Economics*. Free Press, New York.
- Greb, B. W., D. E. Smika, and J. R. Welsh. 1979. Technology and wheat yields in the central Great Plains: experiment station advances. *J. Soil Water Conserv.* 34: 264–268.
- Hazell, P. B. R., and R. D. Norton. 1986. *Mathematical Programming for Economic Analysis in Agriculture*. Macmillan, New York.
- Jacobson, H. K., and M. F. Price. 1991. *A Framework for Research on the Human Dimensions of Global Environmental Change*. International Social Science Council, Paris, France.
- Knop, E. 1987a. Alternative perspectives on community impacting: toward complementary theory and application. *Sociological Inquiry* 57: 273–291.
- _____. 1987b. Subjective and objective assessment of environmental quality. *Free Inquiry in Creative Sociology* 5: 75–80.
- Kraenzel, C. 1955. *The Great Plains in Transition*. University of Oklahoma Press, Norman.
- Lawson, M., and M. Baker, eds. 1981. *The Great Plains in Perspective*. University of Nebraska Press, Lincoln.
- Lee, R. G., R. Flamm, M. G. Turner, C. Bledsoe, P. Chandler, C. DeFerrari, R. Gottfried, R. J. Naiman, N. Schumaker, and D. Wear. 1992. Integrating sustainable development and environmental vitality: a landscape ecology approach. Pages 499–521 in R. J. Naiman, ed. *Watershed Management: Balancing Sustainability and Environmental Change*. Springer-Verlag, New York.
- Lovejoy, S. B., and T. L. Napier, eds. 1986. *Conserving Soil: Insights from Socioeconomic Research*. Soil Conservation Society of America, Ankeny, Iowa.
- Murdock, S. H., F. L. Leistritz, R. R. Hamm, D. E. Albrecht, and A. G. Leholm. 1987. Impacts of the farm crisis on a rural community. *Journal of Community Development Sociology* 18: 30–49.
- Meyer, W. B., and B. L. Turner. 1992. Human population growth and global land-use/cover change. *Annu. Rev. Syst.* 23: 39–61.
- _____. In press. *Changes in Land Use and Land Cover: A Global Perspective*. Cambridge University Press, New York.
- Ottosen, H. W., E. M. Birch, P. A. Henderson, and A. H. Anderson. 1966. *Land and People of the Great Plains Transition Area*. University of Nebraska Press, Lincoln.
- Parton, W. J., D. S. Schimel, C. V. Cole and D. S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.* 51: 1173–1179.
- Parton, W. J., J. M. O. Scurlock, D. S. Ojima, T. G. Gilmanov, R. J. Scholes, D. S. Schimel, T. Kirchner, J.-C. Menaut, T. Seastadt, E. Garcia Moya, A. Kamndrut, and J. I. Kinyamaria. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochem. Cycles* 7: 785–809.
- Parton, W. J., J. W. B. Stewart, and C. V. Cole. 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry* 5: 109–131.
- Paustian, K., W. J. Parton, and J. Persson. 1992. Influence of organic amendments and N fertilization on soil organic matter in long-term plots: model analyses. *Soil Sci. Soc. Am. J.* 56: 476–488.
- Popper, D. E., and F. J. Popper. 1987. The Great Plains: from dust to dust. *Planning* 53: 13–18.
- Rae, A. N. 1976. An empirical application and evaluation of discrete stochastic programming in farm management. *Am. J. Agric. Econ.* 53: 625–38.
- Riebsame, W. E. 1990. The United States Great Plains. Pages 561–575 in B. L. Turner, W. C. Clark, R. W. Kates, J. F. Richards, J. T. Mathews, and W. B. Myers, eds. *The Earth as Transformed by Human Action*. Cambridge University Press, New York.
- _____. 1991. Sustainability of the Great Plains in an uncertain climate. *Great Plains Res.* 1: 132–150.
- Robinson, J. B. 1991. Modeling the interactions between human and natural systems. *International Social Science Journal* 130: 629–647.
- Saarienen, T. F. 1966. Perception of the drought hazard on the Great Plains. Research Paper No. 106, Department of Geography, University of Chicago, Chicago, IL.
- Sala, O. E., W. J. Parton, L. A. Joyce, and W. K. Lauenroth. 1988. Primary production of the central grassland region of the United States: spatial pattern and major controls. *Ecology* 69: 40–45.
- Sanford, R. L. Jr., W. J. Parton, D. S. Ojima, and D. J. Lodge. 1991. Hurricane effects on soil organic matter dynamics and forest production in the Luquillo Experimental Forest, Puerto Rico: results of simulation modeling. *Biotropica* 23: 364–372.
- Schimel, D. S., T. G. F. Kittel, A. K. Knap, R. T. Seastedt, W. J. Parton, and V. B. Brown. 1991. Physiological interactions along resource gradients in tallgrass prairie. *Ecology* 72: 672–684.
- Smika, D. E. 1992. Cereal systems of the North American central Great Plains. Pages 401–412 in C. J. Pearson, ed. *Field Crop Ecosystems*. Elsevier, New York.
- Stern, P. C., O. R. Young, and D. Druckman, eds. 1992. *Global Environmental Change: Understanding the Human Dimensions*. National Academy Press, Washington, DC.
- Strauss, A., and J. Corbin. 1990. *Basics of Qualitative Research: Grounded Theory, Procedures, and Techniques*. Sage Publ., Newbury Park, NJ.
- Taylor, R. G., and R. A. Young. 1993. Some economic impacts of rural-to-urban water transfers: a case study of Crowley County, Colorado. Completion Report No. 174, Colorado Water Resources Research Institute, Fort Collins.
- Turner, B. L., and W. B. Meyer. 1991. Land use and land cover in global environmental change: considerations for study. *International Social Science Journal* 130: 669–679.
- Turner, B. L. II, R. H. Moss, and D. L. Skole. 1993. *Relating Land Use and Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project*. International Geosphere-Biosphere Program, Stockholm, Sweden.
- US Department of Agriculture (USDA). 1989. *The Second RCA Appraisal: Soil, Water, and Related Resources on Nonfederal Land in the United States*. Washington, DC.
- Warrick, R. A., and M. J. Bowden. 1981. The changing impacts of drought in the Great Plains. Pages 111–137 in M. P. Lawson and M. E. Baker, eds. *The Great Plains: Perspectives and Prospects*. University of Nebraska Press, Lincoln.
- Webb, W. P. 1931. *The Great Plains*. Ginn, Boston.
- Worster, D. 1979. *Dust Bowl: The Southern Great Plains in the 1930s*. Oxford University Press, New York.
- Young, R. A., R. M. Longenbaugh, and J. R. McKean. 1982. Energy and water scarcity and the irrigated agricultural economy of the Colorado Ogallala High Plains: direct economic-hydrologic impact forecasts, 1979–2020. Technical Report No. 34, Colorado Water Resources Research Institute, Colorado State University, Fort Collins.