Multiple-Objective Decision Making for Agroecosystem Management

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Multiple-objective decision making (MODEM) provides an effective framework for integrated resource assessment of agroecosystems. Two elements of integrated assessment are discussed and illustrated: (1) adding noneconomic objectives as constraints in an optimization problem; and (2) evaluating tradeoffs among competing objectives using the efficiency frontier for objectives. These elements are illustrated for a crop farm and watershed in northern Missouri. An interactive, spatial decision support system (ISDSS) makes the MODEM framework accessible to unsophisticated users. A conceptual ISDSS is presented that assesses the socioeconomic, environmental, and ecological consequences of alternative management plans for reducing soil erosion and nonpoint source pollution in agroecosystems. A watershed decision support system based on the ISDSS is discussed.

> *In all areas of science, the convergence and integration of information from different points of view, different disciplines, and different approaches are what lead to advances and breakthroughs in understanding.*
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> —Gene E. Likens (1992)

Land and water resource degradation from cropland erosion and nonpoint source pollution have reduced the socioeconomic, environmental, and ecological values provided by agroecosystems in North America. Ninety-six percent of the soil degradation in this region occurs in agroecosystems dominated by crop and livestock production (World Resources Institute 1992). Soil degradation is caused by water and wind erosion, salinization, acidification, waterlogging, compaction, and other factors. Physical and chemical degradation of soils along with heavy use of fertilizers and pesticides contributes to sedimentation and nutrient/pesticide contamination of surface and ground water. Agriculture is a major source of nonpoint source pollution. The U.S. Environmental Protection Agency (EPA 1986) estimates that between 50 and 70% of assessed surface waters are adversely impacted by agricultural nonpoint source pollution.

Cropland erosion and nonpoint source pollution cause significant economic and ecological damage. Excessive cropland erosion decreases soil productivity, which reduces potential long-term crop yields. The economic value of yield losses from topsoil erosion on U.S. cropland is about $3.5 billion per year (Clark, Haverkamp, and Chapman 1985). High rates of erosion and runoff increase sedimentation of water bodies, which raises water treatment costs, reduces hydroelectric generating capacity, and decreases the productivity of terrestrial and aquatic ecosystems. Annual offsite damage from soil erosion in the U.S. has been estimated to be $10 billion excluding damage to aquatic ecosystems (Ribaudo 1989).

Traditionally, management plans/policies for reducing cropland erosion, nonpoint source pollution, and other forms of resource degradation have been evaluated based on single objective approaches. Examples include selecting the resource management plan that maximizes profit or selecting the conservation practices that minimize the cost of achieving a desired reduction in soil erosion or nonpoint source pollution. A common way to compare the micro-level economic and resource impacts of alternative management plans/policies is to express all benefits and costs in monetary units. This approach requires expressing resource impacts in monetary terms by applying nonmarket valuation methods such as travel cost or contingent valuation. Evaluation of resource impacts of macroeconomic activities can be done using natural resource accounting methods. These methods involve accounting for the effects of economic growth on resource depletion by either developing

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separate natural resource accounts or adjusting national income accounts, such as gross national or gross domestic product, for natural resource depletion.

Another approach to the evaluation of resource management plans/policies is multiple-objective decision making (MODEM). Applied to agroecosystems, this approach involves selecting management systems for a farm or watershed that have attributes which maximize the attainment of multiple objectives. This paper has three objectives: (1) to examine the conceptual basis for MODEM; (2) to develop a framework for implementing MODEM that integrates economic, environmental, and ecological objectives and; (3) to illustrate noninteractive and interactive applications of MODEM.

Conceptual Basis

Methods for evaluating resource management plans/policies can be arrayed along a spectrum having the *reductionist method* at one end and the *holistic method* at the other. In the reductionist approach, a particular slice of reality is evaluated from a narrow disciplinary perspective. Reductionism has a long history of use and acceptance in the scientific community. The specialization afforded by reductionist science has advanced the understanding and resolution of a wide range of social issues. A holistic evaluation of resource management practices/policies synthesizes and integrates concepts and information from several disciplines. In this respect, holistic resource management is a systems approach. A holistic approach focuses on the socioeconomic, environmental, and ecological processes that determine the effectiveness and efficiency of soil and water conservation practices and policies. In a holistic approach, the impacts of using a resource conservation practice are examined from a multidisciplinary perspective.

The holistic approach has its share of difficulties. First, it runs counter to the way generations of scientists and practitioners have acquired and applied knowledge. Second, the inherent complexity of the holistic approach requires considerable interaction among the practitioners of several disciplines. Such interaction is difficult and at times frustrating because of differences in theory, methods, and data.

Despite the inherent difficulties of a holistic approach to resource planning and management, it is becoming the leading paradigm for understanding and resolving complex natural and environmental resource problems. Early support for incorporating socioeconomic aspects into holistic resource management was expressed by Schumacher, who made a strong plea for a metaeconomics approach that has the ''aims and objectives from a study of man, and . . . at least a large part of its methodology from a study of nature'' (1973, p. 47). Conventional economics derives much of its methodology from quantitative sciences such as physics and not from the study of nature. Schumacher is critical of this quantitative orientation, noting that ''the great majority of economists is still pursuing the absurd ideal of making their 'science' as scientific and precise as physics, as if there were no qualitative differences between mindless atoms and men made in the image of God'' (ibid., p. 49). Similar criticisms have been levied against conventional economics by Leopold (Tanner 1987), Boulding (1966), Georgescu-Roegen (1971), and Daly (1991). Ecological economics has emerged from such criticism.

The implications of adopting a holistic approach to resource management can be illustrated with regard to a pivotal assumption in economics that humans are motivated by selfishness. This assumption underlies the theory of consumer behavior and the theory of the firm. Daly and Cobb criticize the assumption that households maximize utility and firms maximize profit oblivious to social community and biophysical interdependence: ''What is neglected is the effect of one person's welfare on that of others through bonds of sympathy and human community, and the physical effects of one person's production and consumption activities on others through bonds of biophysical community'' (1989, p. 37).

Adopting a holistic approach to resource management requires sociologists and economists to become more familiar with the biophysical principles governing the natural world and to integrate these principles with socioeconomic concepts in addressing resource management issues. In this framework, socioeconomics is viewed not so much as a self-contained body of knowledge, but rather as a set of concepts that in combination with other scientific principles enhances society's understanding of resource and environmental issues. This viewpoint has been espoused by many contemporary economists including Boulding, Georgescu-Roegen, Norgaard, Daly, and others.

MODEM Framework

A MODEM framework integrates the socioeconomic, environmental, and ecological objectives relevant to agroecosystem management and the underlying processes that influence the attainment of those objectives. Socioeconomic objectives deal with the social and economic aspects of soil and water resource use. Social objectives address attitudes regarding the acceptability of specific management practices or policies and preferences for the three objectives. Economic objectives include the private and social benefits and costs of a management plan or policy. Environmental objectives address how practices and policies affect environmental endpoints such as soil erosion and surface and ground water quality. Ecological objectives encompass the quantity and quality of riparian areas and wetlands and the performance of aquatic and terrestrial ecosystems.

A conceptual framework for MODEM is illustrated in figure 1. The decision maker is an individual whose preferences for socioeconomic (*SE*), environmental (*EN*), and ecological (*EC*) objec-

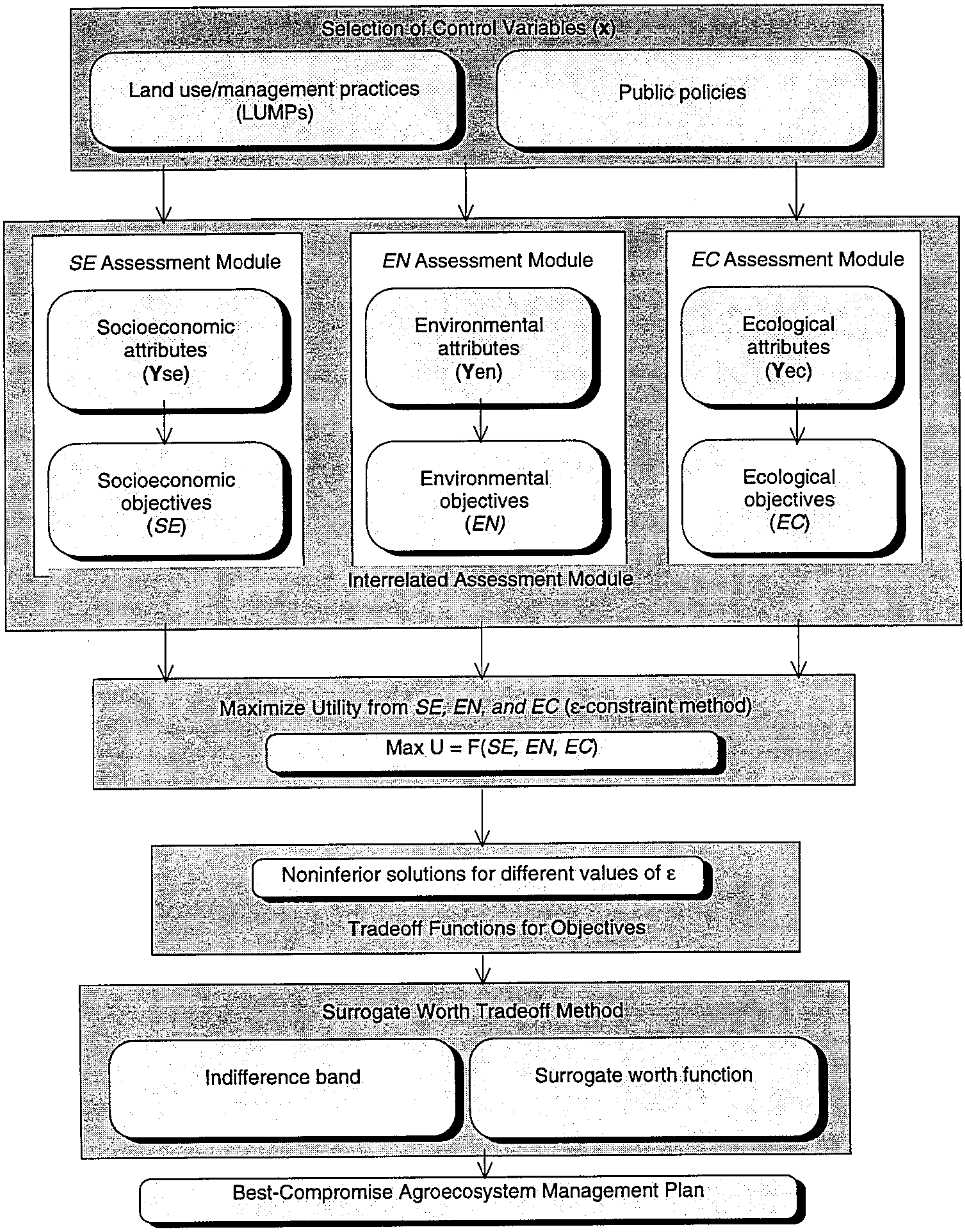

Figure 1. Conceptual Framework for Multiple-Objective Decision Making (MODEM)

tives are summarized by the following utility function:

$$U = U(SE, EN, EC).$$

U is the level of satisfaction provided by the three objectives. Two features of the objectives are noteworthy. First, they are noncommensurate because they have different metrics; the economic objective is measured in dollars, the environmental objective in mass or concentrations of contaminants, and the ecological objective in species richness and diversity. Second, over some range, the objectives are likely to be competitive with one another.

MODEM assumes that a decision maker would select land use/management practices (LUMPs) and favor public policies that maximize the above utility function subject to biogeophysical conditions. Public policy influences the choice of LUMPs by altering their economic benefits and costs. For example, the conservation reserve program favored the temporary retirement of environmentally sensitive lands, and price support programs favor the planting of crops such as corn, sorghum, wheat, and cotton. Green payments would alter the profitability of different LUMSs.

Each objective has a set of attributes that influences the attainment of that objective. If the SE objective is the economic viability of farming, then relevant attributes include the mean and variance in net farm income. If the *EN* objective is surface water quality, then relevant attributes include mass loading or concentration of nutrients (nitrogen and phosphorus), sediment, and chemical oxygen demand in runoff and stream flow. If the *EC* objective is the health of aquatic ecosystems, then relevant attributes include species diversity and richness. Attributes related to the same objective can be aggregated. For example, the Index of Biological Integrity developed by Karr et al. (1986) could be used to present the health of aquatic ecosystems.

Since attainment of an objective depends on the levels of the attributes corresponding to that objective, the utility function can be rewritten as:

$$U = U[SE(\mathbf{y}_{SE}), EN(\mathbf{y}_{EN}), EC(\mathbf{y}_{EC})],$$

where $\mathbf{y}_{SE}$, $\mathbf{y}_{EN}$, and $\mathbf{y}_{EC}$ are vectors of attributes associated with objectives *SE*, *EN*, and *EC*, respectively, and $SE(\mathbf{y}_{SE})$, $EN(\mathbf{y}_{EN})$, and $EC(\mathbf{y}_{EC})$ are utility subfunctions. Maximizing the overall utility is tantamount to finding the most preferred set of values for the utility subfunctions, or equivalently, the most preferred set of attributes. This specification of the utility function is common in multiple-objective optimization problems (Haimes and Hall 1977, Changkong and Haimes 1983, Dinh 1989, Nijkamp and Spronk 1981, Steuer 1986, Haimes et al. 1990).

The level of each attribute is determined by the selection of one or more control variables that include current and alternative LUMPs and public policies for managing agroecosystems. For example, the control variables (LUMPs) for enhancing the *EN* objective of surface water quality in an agricultural area include reducing fertilizer application rates, switching to crop rotations that require less fertilizer, banded application of pesticides, and incorporating buffer strips and wetlands into riparian areas. If MODEM is being applied to a farm or watershed, then the control variables need to be defined for each parcel in the farm or watershed because achievement of the three objectives depends on the spatial configuration of control variables in the farm or watershed. Denoting the control variables for a particular farm or watershed by a vector **x** allows the utility function to be written as:

$$U = U[SE(\mathbf{x}), EN(\mathbf{x}), EC(\mathbf{x})].$$

The constrained optimization problem for the decision maker is to select **x** such that the combination of objectives provided by **x** maximizes the above utility function subject to relevant biophysical constraints.

MODEM at the farm and watershed levels can be evaluated from the viewpoints of farmers and society. It is relatively straightforward to derive a privately optimal, MODEM-based management plan for a farm because there is only one decision maker and hence only one set of preferences to consider. Deriving a management plan for an entire watershed by maximizing a utility function that reflects the preferences for all farmers in the watershed is not straightforward because there is no theoretically acceptable way to aggregate the preferences of different farmers. When it is desirable to bring privately optimal farm management plans in line with socially optimal farm management plans for a farm or watershed (internalizing relevant externalities), potential discrepancies between the two sets of plans need to be identified. Consider how this can be accomplished. First, the privately optimal management plan for each farm in the watershed is derived based on a MODEM-type evaluation. Second, the socially optimal, MODEM-based watershed management plan is derived by treating the watershed as though it were managed by a land planner who represents society's interests. Third, the socially optimal management plan for each farm in the watershed is determined by simply noting the LUMPs selected for each farm in the socially optimal watershed management plan. Fourth, the private and socially optimal management plans for individual farms are compared and the discrepancies noted.

The three objectives in the above MODEM model are interdependent. For example, the ecological objective of aquatic ecosystem health is affected by environmental quality (sediment, nutrient/pesticide concentrations, and chemical oxygen demand in runoff), which, in turn, is influenced by the choice of LUMPS. Each objective would have to be evaluated using an assessment module that determines the attainment level for that objective for various values of the control variables. For example, the environmental assessment module could use one or more water quality models to simulate how different methods and rates of application of fertilizer and pesticides influence nutrient and pesticide concentrations in runoff and leachate.

Although the above constrained optimization problem does not have a unique solution, noninferior solutions can be determined using the ϵ-constraint method developed by Haimes et al. (1971), Cohon (1978), and Cohon and Marks (1993). Noninferior solutions represent efficient combinations of the objectives. The ϵ-constraint method maximizes achievement of a primary objective subject to inequality constraints on the remaining objectives. To illustrate this method, let the primary objective be *SE*. The optimization problem then becomes:

$$\underset{\mathbf{x}}{\text{maximize}}\ SE(\mathbf{x})$$

$$\begin{aligned}\text{subject to: } EN(\mathbf{x}) &\leq \epsilon_{EN}\\ EC(\mathbf{x}) &\leq \epsilon_{EC}, \text{ and}\\ \mathbf{x} &\in \mathbf{X},\end{aligned}$$

where ϵ_{EN} and ϵ_{EC} are upper limits on attainment levels for objectives *EN* and *EC*, respectively, **x** is a set of control variables (resource management plan), and **X** is a set of feasible solutions for **x**. Any solution to this optimization problem is an acceptable solution to the original constrained utility maximization problem. Noninferior solutions to this optimization problem are determined by solving the optimization problem for different values of ϵ_{EN} and ϵ_{EC}. The resulting non-inferior solutions are used to derive tradeoff functions for objectives. A tradeoff function indicates the tradeoff ratio between objectives or the marginal benefit (cost) of an objective due to an additional unit of ϵ. For example, the tradeoff function for the socioeconomic and environmental objectives indicates the extent to which an additional unit of the socioeconomic objective decreases the environmental quality objective. Ma (1993) and Xu, Prato, and Ma (1995) used the ϵ-constraint method to generate tradeoff functions between three objectives (maximum net return, minimum soil erosion, and minimum nitrate available for leaching) for a Missouri farm.

An optimal value of **x**, also called the best-compromise agroecosystem management plan, can be determined from the tradeoff information using the surrogate worth tradeoff (SWT) method developed by Haimes and Hall (1974, 1977). In this method, a surrogate worth function is used to evaluate the desirability of each tradeoff ratio presented to a decision maker. One possibility for the surrogate worth function is to ask each decision maker to assign a value between -10 and $+10$ to tradeoff ratios. The numerical value selected by the decision maker depends on the extent to which a marginal change in the one objective is worth more or less than a one-unit change in another objective. For this scale, -10 indicates a very unfavorable tradeoff, 0 implies indifference regarding the tradeoff, and $+10$ signifies a favorable tradeoff.

An optimal **x** is any noninferior feasible solution that belongs to the indifference band, which is the subset of the noninferior set for which an increase in one objective is equivalent (in the mind of the decision maker) to a decrease in another objective. The subset of solutions in the indifference band makes the surrogate worth functions simultaneously equal to zero for all evaluated tradeoff ratios. The SWT method approximates the **x** that corresponds to the tangency between the tradeoff function and indifference curve.

Applications of MODEM

The MODEM framework can be implemented using noninteractive and interactive approaches. A noninteractive approach involves manually linking the assessment modules in the MODEM model. The linkage is usually done by someone other than the decision maker, such as the developer of the model or someone with technical expertise in applying the assessment modules. In this respect, a noninteractive approach is appropriate for efficiency assessments of farming systems.

While a noninteractive MODEM is useful in identifying the most efficient set of farming systems for achieving socioeconomic, environmental, and ecological objectives, it is not likely to be used by unsophisticated decision makers. Advances in economic modeling, environmental simulation, geographic information systems (GIS), and remote sensing make it possible to translate a MODEM model into an interactive, spatial decision support system (ISDSS). An ISDSS is a knowledge-based computer program that integrates data, information, and models for the purpose of identifying and evaluating solutions to complex problems involving spatially distributed information (Djokic 1993). Since a noninteractive approach is designed to provide solutions, it is the appropriate approach for designing an ISDSS. Leng (1991) points out that a decision support system (DSS) should be designed to assist decision makers in performing their task. Potential benefits of an ISDSS for water resources planning were identified by Loucks and Fedra (1987). They note that, unlike traditional offline, noninteracitve approaches, an ISDSS allows a decision maker to derive solutions based on his/her own objectives and subjective judgment in an interactive learning and decision-making process.

An ISDSS has three basic objectives: (1) to supply information based on existing data and scientific evidence; (2) to help design alternatives and assess consequences of new management plans or policies; and (3) to help evaluate and compare alternative management schemes (Fedra et al. 1993). Resource planners, managers, and specialists can use an ISDSS to develop a best-compromise management plan for an agroecosystem.

Noninteractive Applications

Farm-Scale Evaluation. Ma (1993) used a multiple-objective mathematical programming model to determine efficient combinations of three objectives: maximum net return (*NR*), minimum soil erosion (*ER*), and minimum nitrate available for leaching (*NL*) achieved by six farming systems for a case study farm located in Goodwater Creek watershed in northern Missouri. This watershed is the site of the Missouri Management Systems Evaluation Area (MMSEA) project. The six farming systems, described in table 1, involve four crops (corn, soybeans, sorghum, and wheat). The farm is 1,022 acres and contains four major soil types (Adco, Leonard, Mexico, and Putnam). *ER* was estimated using the Universal Soil Loss Equation (Wischmeier and Smith 1978) and *NL* was simulated using the Nitrogen for Leaching and Economic Analysis Package (Shaffer, Halverson, and Pearce 1991). Prato, Xu, and Ma 1994 give a more detailed explanation of the model. Net return per acre for each farming system (last column in table 1) was based on 1991-92 input and yield data from three fields in the case study farm and replicated experimental plots in Goodwater Creek watershed. Comparing the net returns for the six farming systems shows that the ranking of farming systems from highest to lowest net return per acre is: FS1, FS4, FS6, FS2, FS3, and FS5.

No single farming system achieves all three objectives. FS1 and FS6 have relatively high *NR*s and high *NL*s. FS4 has the second highest *NR* and low *NL*. FS1 and FS5 are inefficient over the entire range of objectives. FS1 is inefficient because it has a high nitrogen application rate, which increases *NL*. FS5 is inefficient for two reasons. First, it has the lowest yields for corn and soybeans, which result in a low *NR*. Second, it utilizes a high nitrogen application rate, which results in a high *NL*.

Solution values for *NR*, *ER*, and *NL* and the optimal acreage for the six farming systems are

Table 1. Description of MMSEA Farming Systems, 1991–92[a]

Farming System	Crop Rotation	Yield (bu/acre)	Tillage System	Nitrogen Application Rate	Herbicide Application Rate	Net Return ($/acre)
FS1	Corn	116	Minimum	High	High	130
	Soybeans	37				
FS2	Sorghum	109	Minimum	Medium	Medium	95
	Soybeans	35				
FS3	Corn	95	Minimum	Low	Low	92
	Soybeans	36				
	Wheat	42				
FS4	Corn	97	Ridge	Low	Low	115
	Soybeans	33				
FS5	Corn	93	No-Till	High	High	83
	Soybeans	33				
FS6	Sorghum	119	Miminum	High	High	111
	Soybeans	34				

[a] MMSEA stands for Missouri Management Systems Evaluation Area. For a complete description of these farming systems, see Alberts, Kitchen, and Prato (1995).

used to estimate the efficient tradeoff function for the three objectives. These functions indicate that the economic objective (*NR*) is competitive with the erosion (*ER*) and water quality (*NL*) objectives, and the erosion (*ER*) and water quality (*NL*) objectives are competitive with one another (Ma 1993). A competitive relationship means that increasing (decreasing) one objective causes the other objective to decrease (increase). Tradeoffs imply that economic and environmental policies designed to enhance one environmental objective should simultaneously consider impacts on both the economic objective and other environmental objectives.

Watershed-Scale Evaluation. Wu (1994) utilized a chance-constrained programming (CCP) model to determine how much of the acreage in Goodwater Creek watershed should be planted to each of six farming systems so as to maximize watershed net returns while achieving specific reductions in sediment yield (*SY*) and soluble nitrogen concentration in runoff (*SN*) at the outlet of the watershed. This approach applies the ϵ-constraint method at the watershed level and assumes that selection of LUMPs is made by a single land planner. The socially optimal acreage derived in this manner is not likely to be optimal from the viewpoint of individual farmers. More details about the CCP model are given in Prato and Wu (1995).

The impacts of specific reductions in *SY* and *SN* are determined by applying increasing percentage reductions to the simulated baseline values of *SY* and *SN*. The latter are determined assuming FS1 is used throughout the watershed. FS1 is chosen as the baseline farming system because it provides the highest net return per acre of the six farming systems. Farming systems used in the watershed-scale evaluation are the same as those used in the farm-scale evaluation (table 1) except for FS6, which is a grass-legume mixture that uses no nitrogen or herbicides and provides a net return of $35 per acre. Simulated values of *SY* and *SN* are derived using the AGNPS model (Young et al. 1987). AGNPS is a distributed parameter model that simulates sediment, runoff, and nutrient transport for alternative LUMPs within an agricultural watershed. It is a storm event–based model that requires dividing the watershed into square, equal-sized cells. Twenty-two input parameters need to be specified for each cell. AGNPS generates cell and watershed values for erosion, runoff, sediment, mass and concentrations of nutrients and pesticides, and chemical oxygen demand in surface water. It does not simulate the effects of alternative LUMPs on groundwater.

Net return per acre for each farming system depends on crop and input prices, crop yield, and input use. Crop and input prices are five-year average (1987–91) market prices for central and north-central Missouri. Crop yields depend on soil type, farming system, and weather (frequency, duration, and intensity of storm events). Since weather is stochastic, crop yields are stochastic. Input use for a given farming system is treated as nonstochastic.

Variation in *SY*and *SN* for a given farming system is related to changes in weather. This variation was determined and utilized as follows. First, the AGNPS model was run for each of sixteen equally spaced intervals for maximum twenty-four-hour precipitation during the 1949–91 period. In these runs, one farming system at a time was used throughout the watershed. Second, the AGNPS results for the sixteen runs were used to calculate the weighted average and variance of SY and SN for each farming system. Weights equal the frequency of occurrence of precipitation events in the sixteen intervals. The mean and standard deviation of net return per acre and the weighted average mean and standard deviation of *SY* and *SN* for each farming system are given in table 2. Third, the means and standard deviations for *NR*, *SY*, and *SN* were used in the CCP model to determine the amount and location of acreage in the watershed that should be

Table 2. Net Return, Sediment Yield, and Soluble Nitrogen Concentration in Runoff, Goodwater Creek Watershed

	Net Return ($/acre)		Sediment Yield[a] (tons)		Soluble Nitrogen[a] (ppm)	
Farming System	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
FS1	133	128	1,436	1,356	12.7	4.7
FS2	89	62	1,455	1,352	4.7	1.4
FS3	89	62	1,046	972	7.8	2.9
FS4	120	96	1,111	1,029	8.3	2.6
FS5	84	88	459	403	5.7	2.2
FS6	35	0	226	185	1.0	0.05

[a] Weighted average of simulated values given by AGNPS model.

devoted to each farming system so as to maximize watershed *NR* subject to specific reductions in *SY* and *SN*.

Application of the CCP model requires specifying reliabilities for achieving maximum watershed *NR* and reductions in *SY* and *SN*. Two reliability levels were used for *NR*: 50% represented risk neutral and 95% represented risk averse preferences. Four reliability levels were selected for *SY* and *SN* reductions: 50, 90, 95, and 97.5%. These are the same values used by Milon (1987) and Braden, Larson, and Herricks (1991).

Results of the watershed-scale evaluation indicate that the mean and standard deviation of *NR* and *SN* are highest for FS1 and of *SY* are highest for FS2. As expected, FS6 has the lowest mean and standard deviation for *NR*, *SY*, and *SN*. A Friedman test leads to rejection of the hypothesis that the six farming systems have uniform water quality effects. For all net return and water quality reliability levels evaluated with the CCP model, *NR* decreases at an increasing rate as *SN* or *SY* decreases. This indicates tradeoffs between *NR* and *SN*, and *NR* and *SY*.

The CCP results also show that achieving large reductions in *SY* or *SN* with high reliability would necessitate major changes in farming systems and/or reductions in planted acreage and watershed *NR*. For example, a 70% reduction in *SY* would require idling between 12 and 69% of the cropland acreage and using FS5 on the remaining acreage in the watershed. A 70% reduction in *SN* would require idling between 23 and 30% of the cropland acreage and using FS2 on the remaining acreage in the watershed. Farming systems that were efficient in reducing *SY* were inefficient in reducing *SN*.

Interactive Approach

This section describes the conceptual basis for a multiple-objective watershed policy assessment tool (MOWPAT) based on the MODEM framework illustrated in figure 1. MOWPAT is designed to allow users to determine spatially efficient arrangements of LUMPs in an agricultural watershed for reducing erosion and nonpoint pollution. LUMPs considered by MOWPAT include crop rotations; tilage practices; conservation practices such as terraces; pollution prevention practices such as timing, rate, and method of application of fertilizers and pesticides; and other landscape features such as grass waterways, riparian buffer strips, and wetlands. MOWPAT consists of three assessment modules: socioeconomic, environmental, and ecological. Each of these modules is described below.

Socioeconomic Module. The socioeconomic module evaluates the social and economic impacts of farm and watershed management plans. Social aspects enter MOWPAT in two ways. First, a decision maker's attitudes toward the multiple objectives associated with a watershed are represented by the decision maker's preferences for objectives that affect the decision maker's selection of a best-compromise management plan. For example, if a decision maker places a high priority on income, then a management plan that maintains or increases income would be favored. Second, a decision maker's attitudes toward specific LUMPs influence the control variables that are acceptable to the decision maker. For example, if a decision maker opposes conversion of agricultural land to a riparian buffer strip or wetland, then that decision maker would not favor a management plan that incorporates these land uses. In this case, conversion of cropland to a buffer strip or wetland is not an acceptable control variable. Such restrictions are used to define admissible control variables (**X**) for decision makers.

The economic component of MOWPAT calculates net returns for alternative LUMPs under various public policies. Net return is calculated as follows. Let RH_{ijk} be annual net return per acre for LUMP i on field j in farm k, RS_k total annual net return for farm k, and RW total net return for the entire watershed.

Annual net return equals gross return minus total variable cost (c) when LUMP i is used on field j. For example, net return for crop rotation i on field j in farm k is:

$$RH_{ijk} = \sum_{t=1}^{T} (r_{ijkt} - c_{ijkt})/(1 + r)^{-t}$$

where r_{ijkt} is gross return per acre with crop rotation i on field j in farm k in year t, c_{ijkt} is variable cost of crop production per acre with crop rotation i on field j in farm k in year t, r is the discount rate, and T is the planning horizon.

Annual net return for farm k is the sum of net returns for all fields located on the farm:

$$RS_k = \sum_{i=1}^{m} \sum_{j=1}^{n_k} A_{ijk}\, \delta_{ij}\, RH_{ijk},$$

where A_{ijk} is the acreage in LUMP i on field j in farm k, $\delta_{ij} = 0$ or 1, $\Sigma_i\, \delta_{ij} = 1$ to ensure that only one LUMP is used per field, n_k is the number of fields in farm k, and m is the number of LUMPs.

Annual net return for the watershed is the sum of annual net returns over all farms in the watershed:

$$RW = \sum_{k=1}^{K} RS_k,$$

where K is the number of farms. The above net return variables are used to measure attainment of the economic component of the socioeconomic (SE) objective. If the MODEM approach is applied to private decision makers on individual farms, then RS_k should be maximized. However, if the MODEM approach is applied to social decision makers in a watershed, then RW should be maximized.

Environmental Module. The environmental module contains two simulation models: AGNPS and SWAT. AGNPS is described above. The SWAT model simulates the effects of alternative agricultural management practices on erosion, runoff, and water quality in rural basins (Arnold et al. 1994). The model is physically based and operates on a daily time step. It is capable of simulating results over extended periods of time for the entire basin and for subbasins. Outputs generated by the SWAT model include crop yields, erosion, sediment, surface runoff, groundwater and lateral flow, and nutrient and pesticide concentrations. The advantage of SWAT over AGNPS is that it provides output summaries for any desired period of time (day, week, month, or year) and handles groundwater. MOWPAT uses a geographic information system (GIS) to reduce the time and labor needed to collect, process, and manipulate the input parameters for AGNPS and SWAT. Output from AGNPS and SWAT are used to compare environmental effects of LUMPs relative to a baseline. SWAT has been utilized in Goodwater Creek watershed to evaluate the water quality impacts of alternative farming systems to reduce atrazine contamination of surface water (Heidenreich, Zhou, and Prato 1995).

Ecological Module.[1] LUMPs occurring in upland areas of a watershed influence sedimentation, pesticide loading, and water temperature, which in turn influence the health of fish and invertebrate communities (Rabeni 1992). Basin-wide environmental assessments are crucial for management of stream biota (Ryder and Karr 1989). However, relatively little research has been done to relate LUMPs outside riparian areas to stream biota. The few attempts are primarily for forested watersheds (Joyce et al. 1990). Increasing the spatial and temporal scale invariably adds to the complexity of evaluating the response of the biota to watershed activities but is essential to understanding the ecological consequences of alternative LUMPs and public policies.

It is difficult to experimentally quantify the impacts of alternative LUMPs on stream biota for several reasons. First, many impacts are cumulative and slow acting, showing their effects on a temporal scale that is not usually examined. Second, land use and channel modifications in watersheds have caused loss of channel complexity and dynamic equilibrium so that a more simplified, usually more unstable, habitat is common. Investigators rarely measure these relatively slow but significant and continually changing habitat events. Third, it is not practical to conduct experiments for entire watersheds.

The ecological module is used to simulate how in-stream biological characteristics related to fish and invertebrate communities respond to changes in water quantity and quality (mean flow, stability of flow, peak flow, nutrients, dissolved oxygen, sedimentation, and temperature) resulting from different LUMPs and public policies. Fausch, Hawkes, and Parsons (1988) have reviewed models that are suited for such simulations. Except for stream temperatures, inputs to the ecological model are the outputs from the environmental simulation models (AGNPS or SWAT). Ecological performance is evaluated in terms of structural endpoints in the stream, namely, species composition for fish and invertebrate communities. Evaluation is based on simple quantitative models that relate fish community structure to flow conditions, siltation, dissolved oxygen, and summer water temperatures. Such models have been developed for northern Missouri headwater streams by Berkman and Rabeni (1987), Samle and Rabeni (1995), and Rabeni and Smale (in press). Models for invertebrate response to these environmental variables have been developed using empirical data from Missouri streams.

Data on community structure can be combined with laboratory or literature-derived environmental tolerance values for individual taxa to compute a stream biological integrity index, such as Karr et al.'s IBI (1986) for fish, and Hilsenhoff's biotic index (1982) for invertebrates. The IBI index is a convenient way to measure how fish and invertebrate communities respond to changes in LUMPs and public policies. Since the index is easy to understand, it is particularly well suited for use in decision support systems.

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[1] This section was contributed by Dr. Charles Rabeni, National Biological Survey, University of Missouri-Columbia, Columbia, Missouri.

The major value of MOWPAT is that it links changes in LUMPs and public policies to changes in economic (net return) and environmental (soil and water) conditions, and changes in environmental conditions to changes in the proximate habitat conditions of the stream. In addition, it simulates how changes in habitat conditions are likely to influence the performance of fish and invertebrate communities as indicated by species richness and diversity and by biological integrity. Socioeconomic, environmental, and ecological models are integrated in the ISDSS using a GIS.

Application of Interactive Approach

Coordinated resource management of a watershed requires the simultaneous consideration of biophysical and socioeconomic interrelationships and impacts. Addressing these considerations requires integration of a large amount of spatial information and knowledge in a rational framework. The watershed management decision support system (WAMADSS) makes complex and technical information and knowledge available to decision makers in a user-friendly graphical user interface (GUI). WAMADSS implements the socioeconomic and environmental assessment modules of the MODEM framework depicted in figure 1.

WAMADSS is used to identify the relative contribution of subwatershed areas to agricultural nonpoint source pollution and to evaluate the effects of alternative LUMPs on farm income, soil erosion, and surface water quality at the watershed scale. LUMPs included in WAMADSS are crop rotations, tillage practices, conservation practices (grass waterways, terraces), pollution prevention practices (timing, rate, and method of application of fertilizers and pesticides), and other landscape elements such as improved vegetative cover in riparian areas. Users with little or no experience in economic-environmental modeling can do watershed planning and management with WAMADSS.

WAMADSS has three major components: a GUI, a GIS, and a modeling system. The GUI provides access to the GIS and modeling system. It contains menus that allow the user to select LUMPs, parameters and evaluation criteria needed to run WAMADSS. A menu provides an interactive interface for entering all the parameters needed to execute a complex operation. The user provides information (filling in blanks, checking boxes, or answering questions) by interacting with visual objects called widgets. A GIS significantly improves the user's ability to manipulate the spatial and nonspatial data needed to evaluate alternative watershed management plans. This approach enhances the ''best judgment'' decisions offered by conventional environmental models such as AGNPS.

The modeling system consists of an environmental module and an economic module. The environmental module uses AGNPS to simulate erosion, sediment, runoff, and nutrient (nitrogen and phosphorus) transport for individual storm events. The economic module evaluates the effects of a particular spatial configuration of LUMPs on annualized net returns at the field and watershed scales. A spatial configuration refers to the LUMPs applied to each and every field in the watershed as specified by the user(s). WAMADSS calculates annualized net return for a field or watershed using the Cost and Returns Estimator (CARE). The spatial data needed to estimate annualized net return include set-aside requirement, total acreage per field, planted acreage per field (total acreage times proportion planted), initial crop yields, and cost of production. The last is estimated based on crop yield, LUMP and average costs of farm labor, fertilizer, pesticides, fuel, machinery, and equipment.

All the parameters required for the economic and environmental modules are stored as relational tables and accessed through the GUI. Some parameters are based on physical attributes extracted from the various layers (hypsography, land use, soils, hydrology), while other parameters are based on input elicited from the user via the GUI. WAMADSS allows the user to specify the criteria used to evaluate watershed management plans. With the results of WAMADSS, the user can modify the LUMPs until a desired management plan is achieved.

The three components that comprise WAMADSS are accessed from one common interface. Specifically, AGNPS and CARE are linked to ARC/INFO via the ARC Macro Language (AML). AML is the programming language used to interface the models in a seamless decision support system framework. This programming language handles all activities, including generating input files, executing the models, and viewing results in the GIS. In terms of input parameter generation, AML programs are used to create the GUI for entering model input parameters and to transform input parameters from the GIS to an AGNPS- or CARE-compatible input file format. WAMADSS permits the end user to modify land use activities by prompting the user through a series of menus that are used to update the parameters for the selected LUMPs.

To illustrate the functionality of WAMADSS, consider how it might be used to evaluate the water quality and economic impacts of converting riparian cropland to riparian buffer strips for given a rainfall event. The user first selects the width of the proposed riparian buffer strip. Then a global selection is made of all fields bordering a stream, and a riparian buffer width is assigned to those fields. All land use–related parameters are then updated to reflect the newly selected land use activity. Specifically, the curve number, surface condition constant, C-factor, Manning's roughness coefficient, pesticide and fertilizer indicators, COD level, and cost and returns are modified to reflect the presence of a riparian buffer strip. Most of these parameters are automatically updated using the programming language in the GIS. AGNPS and CARE are then executed for this scenario and the results are displayed in graphical and tabular format.

Summary

MODEM provides a holistic framework for evaluating the impacts of alternative land use/management practices and public policies on economic returns, environmental quality, and agroecosystem health. The MODEM framework incorporates the socioeconomic, environmental, and ecological objectives of interest to resource owners, planners, and managers, and identifies tradeoffs among competing objectives. One of the challenges of utilizing a MODEM framework is that it requires coordination among scientists from several disciplines, which can be time consuming and frustrating. Implementation of the MODEM framework can be achieved using either a noninteractive or an interactive approach. A noninteractive approach manually links the socioeconomic, environmental, and ecological assessment modules relevant to decision making in agroecosystems. An interactive approach automatically links the assessment modules using a spatial decision support system. An interactive MODEM framework allows local decision makers to develop a resource management plan for an agroecosystem that is consistent with their preferences for socioeconomic, environmental, and ecological objectives.

This paper presents two examples of the noninteractive MODEM framework. The first example determines the efficiency of farming systems for achieving three objectives using data from a case study farm in north-central Missouri. The three objectives are reducing soil erosion, decreasing nitrate available for leaching, and increasing net returns. None of the six farming systems was uniformly superior in achieving all three objectives. Tradeoff functions for the three objectives indicated that increasing net returns is competitive with decreasing soil erosion and reducing nitrate available for leaching, and that reducing erosion is competitive with decreasing nitrate available for leaching.

The second example utilizes a chance constrained programming model to determine the most economically efficient spatial distribution of six farming systems for reducing sediment yield (*SY*) and soluble nitrogen concentration in runoff (*SN*) in an agricultural watershed. Results of this watershed-scale evaluation indicate that for all net return and water quality reliability levels considered, watershed net return (*NR*) decreases at an increasing rate as *SN* or *SY* decrease which indicates tradeoffs between *NR* and *SN*, and *NR* and *SY*. Additionally, farming systems that were efficient in reducing *SY* were inefficient in reducing *SN*. Achieving large reductions in *SY* or *SN* with high reliability would require major changes in farming systems and/or reductions in planted acreage and watershed *NR*.

Both applications of the noninteractive approach identify efficient farming systems for achieving objectives selected by the analyst. A more realistic, albeit more time-consuming extension of the noninteractive applications given in this paper, is to utilize objectives selected by the farmer. When a farmer's objectives and preferences for objectives are used in determining the efficiency frontier and indifference curve, respectively, the resulting optimal choice of farming systems is more realistic.

Preliminary progress is reported for a prototype noninteractive, watershed-scale model that integrates the economic and environmental assessment modules of a MODEM model. Integration is achieved using a graphical user interface developed using the ARC Macro Language in the ARC/INFO geographic information system. The prototype model significantly reduces the time required to evaluate the economic and environmental impacts of implementing alternative land use and management practices in an agricultural watershed. The prototype model is being expanded to handle ecological impacts of changes in land use and management practices and multiple-objective decision making at the farm and watershed scales.

The full power of the MODEM approach is achieved when it is implemented in the form of an interactive spatial decision support system (ISDSS), which derives a solution (choice of farming systems) determined by the tangency between the efficiency frontier for objectives specified by the user and preferences for those objectives elicited from the user. Development of such an ISDSS is quite challenging because it involves processing of information about objectives and preferences for objectives in an interactive computer session.

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