MODELLING TRADE-OFFS BETWEEN WATER QUALITY AND PROFITS IN AGRICULTURAL WATERSHEDS.

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Abstract

As agricultural activities have the propensity to degrade water quality within a watershed, it is important to strike a balance between unchecked tilling of soil (and resultant non-point source pollution) and economic profits in order to maintain overall water quality. Spatial Decision Support Systems (SDSS) provide decision-makers with a computerized environment within which to model these trade-offs in order to ensure the acceptance of specific conservation policies by individuals. As an example, there has been a concerted effort to manage amount of soil erosion from agricultural fields through legal means in the state of Illinois, USA. However, compliance with the mandate to reduce soil erosion has been problematic because of negative impacts on a farmer's profitability. This paper describes the use of an SDSS to target compensatory payments towards reticent farmers in order to bring them into compliance by offsetting their economic losses. Further, this paper also describes the use of recent advances in Artificial Intelligence technology, in the form of "Intelligent Agents", to build improved models of human decision-making behavior that simulates acceptance of compensatory payments by farmers within the Cache River watershed of southern Illinois.

1. Introduction

The need for managing the impact of anthropogenic activities on rivers and lakes has increased during the last two decades as societies recognized the value of freshwater resources to support growing populations and economic development. In the United States, and other countries, emphasis on the protection and sustainable use of existing water resources has forced water planners to seek out methods of minimizing impacts on these resources, and finding a balance between both human and ecological needs for water.

In most regions of the world, particularly those with intensive agricultural practices, there is often a trade-off between maximizing land under cultivation and preserving the water quality of streams in agricultural watersheds. This is nowhere more evident than in the U.S. With the considerable successes that have been achieved in controlling industrial pollution, especially point-source water pollution, environmental issues in the U.S. are increasingly focused on watersheds. Because 70% of the land in the U.S. is held privately, with at least 90% of this total outside metropolitan areas [1], non-point source pollution (in the form of sediments and agricultural chemicals) from privately owned rural land is an issue of large and increasing importance. Often, these issues can only be addressed by managing landscapes at watershed scales.

In order to reduce the sediment and nutrient loads of agricultural streams, legislation (such as the Conservation Reserve Program or CRP) has been created in the U.S. to take croplands out of production by providing cash incentives. CRP payments are provided by the U.S. Department of Agriculture to farmers in order to retire highly erodible parcels of land from active farming for a period of ten years. However, since the rental rate provided to the farmers is usually below market value of what a farmer could derive from farming that parcel, the acceptance of this
payment structure is not always 100% and the success of this program is dependent upon the attitude of local farming communities. Further, given that there is only a finite amount of funds available for these programs, tax dollars are wasted if croplands that enroll under CRP do not maximize benefits (i.e., reductions in sediment and nutrient load) in comparisons to the costs involved. Therefore, a better alternative would be to create higher levels of payments specifically targeted towards those that have the greatest potential to degrade water quality.

Computer modeling and simulation can be used to assist decision makers maximize the distribution of funds available under CRP. In this respect, computer simulation has two perceived uses:

a. It can be used to identify, and hence target conservation payments to specific farms in the watershed that optimize profitable crop distributions, while subject to limitations of allowable sediment and nutrient runoffs from farm fields for the watershed.

b. It can be used to determine an optimal payment structure that could potentially induce farmers whose land-holdings are targeted for reduced sediment erosion and nutrient runoff to enroll in CRP.

The use of computer simulation for the first of the two above-stated uses can be demonstrated through a Spatial Decision Support System (SDSS) developed for the Cache River, a rural watershed in Southern Illinois. The goal of this SDSS was to use a linear program (GEOLP) to determine crop distributions within the Cache river watershed that maximized profits for farmers in the watershed, when subject to constraints of a fixed amount of soil loss from specific soil types per year. Other variables in the model included current crop prices, and constraints of available labor and machinery for individual farmers.

The second of the above-stated uses is demonstrated through the development of an “Intelligent Agent” based system to model the behavior of farmers in the rural southern Illinois watershed. “Intelligent Agents” are computer software entities that attempt to mimic the behavior of individuals and their responses in a dynamic world. These agents were subsequently utilized to determine the willingness of landholders in the watershed to enroll in a conservation program such as CRP.

2. Overview of Spatial Decision Support Systems (SDSS)

Spatial Decision Support Systems (SDSS) were created to support the analysis of semi- and un-structured spatial problems (i.e., complex spatial problems where it is not possible to completely define a problem or fully articulate the objectives of the solution in mathematical terms). Spatial decision support systems extend the spatial analytical capabilities available in existing GIS. SDSS owe their origin to Decision Support Systems (DSS) developed by researchers in management science. According to Sprague [2], DSS:

a. tend to be aimed at solving semi- and un-structured problems that upper level managers typically face;

b. attempt to combine analytical modeling with traditional data storage and retrieval functions to solve semi-structured problems;

c. are designed to be user-friendly and accessible to decision makers with minimal computer experience; and

d. emphasize flexibility and adaptability to accommodate changes in decision-making approaches.

Extending the definition of a DSS presented above, Densham [3] suggested that a GIS software package can be considered a decision support technology (i.e., SDSS) if the system has a user-friendly front-end and seamlessly incorporates spatial analytical modeling software.

In recent years, several SDSS developments have been reported in the GIS literature that integrate GIS and modeling software and provide support to decision-makers for water resources management. The NELUP DSS [4] was developed to study the impact of policy changes (at a
global, continental, national, regional, county or local level) on the rural landscape, agriculture and environment, and its impact on river water quality in the U.K. NELUP DSS integrates three categories of models within its framework: agricultural economic models, ecological models and hydrological models, and uses them to estimate the impact of specific agricultural policy. The Modular Modeling System (MMS) [5] was developed to help decision-makers manage watersheds and multipurpose reservoirs. It utilizes a variety of compatible model components that can be integrated together to simulate water, energy, and biogeochemical processes.

3. Targeting Conservation Payments to specific farms: Cache River SDSS

The Cache River SDSS, created for the Cache River watershed of southern Illinois (Figure 1), integrates a Linear Program (LP) based farm model (GEOLP) and the AGNPS hydrologic model within ArcView GIS to model the ecological and economic impacts of implementing the Illinois Erosion and Sediment Control law of 1980. According to this law, often referred to as the “T by 2000” program, sediment loss from all crop fields in Illinois were to be reduced to a “tolerable” level T by the year 2000 [6]. Tolerable soil loss (T), measured individually in tons/acre for each soil type, is defined as the maximum amount of material that can be eroded per acre without a reduction in long-term soil productivity.

![Figure 1: Location Map of southern Illinois showing the Cache River watershed](image)

One of the issues hindering adoption of “T by 2000” program by farmers, however, is the loss in farm income that it entails. Most often, shifting from conventional to no-till or other forms of conservation tillage means lower crop yields, and therefore lower profits. In the face of already
low farm incomes in the southern Illinois region (compared to the rest of the U.S.), compliance with the "T by 2000" mandate faced stiff resistance from the farming community.

Therefore, the goal of the SDSS described here was to help decision-makers (such as U.S. Department of Agriculture district soil conservation officers) determine the nature and spatial distribution of economic losses suffered by farmers in the Cache River watershed if they adhered to the "T by 2000" program, and to develop a compensation strategy. Further, the SDSS was also designed to determine the impact of an altered landscape on sediment erosion and transport within the watershed. To achieve these goals, two models, a spatially enhanced Linear Program (LP) called GEOLP, and a watershed-based hydrological and sediment-transport model called AGNPS, were integrated with a desktop GIS (ArcView© 3.2) software (Figure 2).

GEOLP spatially extends the farm model developed by Kraft and Toohill [7], and maximizes economic profits for a parcel of land, subject to the constraints:

- crop yields on available soil-types,
- current market prices,
- long-term sustainability of the soil based on tolerable soil loss 'T', and
- available labor and machinery.

Therefore, GEOLP can be used to determine the most profitable crop-types that can be grown on a parcel of land at different levels of allowable soil loss. For example, GEOLP can predict the most profitable options for a farmer when s/he is allowed 12 tons/ha of soil loss as compared to 24 tons/ha. Certainly, crops grown under more stringent soil loss constraints (i.e., 12 tons/ha) are likely to be less profitable. Further, GEOLP is designed to determine the location and extent of economic losses suffered by farmers in the watershed as a result of implementing the soil loss constraints as part of the "T by 2000" mandate. For example, Figure 3 shows optimal crop distributions for the Big Creek watershed (a sub-watershed of the Cache River) with and without adherence to "T by 2000". Figure 4 indicates the percentage losses suffered by farms located in different parts of the Big Creek watershed as a result of adherence to the "T by 2000" program.
Figure 3: Crop distribution for Big Creek sub-watershed impacted by “T by 2000”

Figure 4: Percentage loss in income resulting from implementation of the “T by 2000” program
AGNPS (or Agricultural Non-Point Source Model) is an event-based, distributed-parameter model designed to simulate hydrology, erosion, and the transport of sediment and chemicals through a watershed [8]. The spatial pattern of model parameters is captured using a grid-based data structure (i.e., raster format). As input, AGNPS requires data relevant to landform, soil and land cover for each cell. Erosion is calculated using a modified form of the universal soil loss equation expressed in terms of rainfall energy intensity, soil erodability, slope length, slope, cover factor, support practice factor, and slope shape. As output, AGNPS provides an estimate of the runoff volume and sediment yield for each cell in the watershed, and estimates of basin-level sediment and nutrient yields.

The altered landscape resulting from implementation of the "T by 2000" law (as generated by GEOLP) is used as the landuse/landcover input into AGNPS. A sample AGNPS output file, depicting the sediment yield (in tons) for the Big Creek watershed following a simulated 1.5 inch, 6 hour rainfall, is shown in Figure 5.

![Figure 5: Sediment Yield for Big Creek Watershed (Simulated rainfall of 1.5 inches over 6 hours)](image)

Using this tool, decision-makers can determine the amount of economic losses suffered by the various farms in the Big Creek watershed as they adopt soil conservation measures. For example, when soil loss constraints are tightened, the amount and location of economic losses within the watershed changes, and can be estimated by GEOLP (refer to Figure 4). This
knowledge is then used to target a compensation strategy, such as CRP, towards the affected farmers. Further, the crop distribution map (effectively, a landuse/landcover map) produced by GEOLP during the simulation can be used by AGNPS to generate estimates of non-point source (sediment, nutrient and pesticide) pollution entering Big Creek. Improvements in non-point source pollution obtained by introducing soil loss constraints can also be compared and evaluated against an unconstrained scenario.

4. Modeling adoption of CRP payments by farmers using "Intelligent Agent" technology

In the Cache River SDSS described above, neoclassical economic theories and profit-maximizing computer models such as linear programming (i.e., GEOLP) were used to model the behavior of farmers. However, seminal work by Simon [9] on bounded rationality, and other research, indicates that farmers include several non-economic rationales while making decisions about agricultural activity on their farms. Many individuals are risk-averse and tend to take decisions based on past experiences or observation of success in their surroundings [10]. Factors such as maintaining a rural lifestyle and conserving soil are sometimes as important to a farmer as having a profitable agribusiness [11]. In most cases, these attitudes reflect an underlying set of physical, social and economic characteristics (including age, income, soil quality and size of holding). Consequently, individual farmers have different attitudes towards adopting Conservation Reserve Payment (CRP) payments.

It is reasonable, therefore, to assume that existing neoclassical economic models (such as the use of GEOLP to model decision-making behavior of farmers) misrepresent the behavioral traits of most farmers. An alternative is to use "Intelligent Agents" to better represent the decision-making characteristics of individual farmers.

Intelligent Agents (or simply "agents") are software entities that share the following four properties [12]: (a) autonomous behavior, (b) ability to sense their environment, (c) ability to act upon their environment, and (d) rationality. Agents have been utilized to model a variety of individual and interactive human behavior within GIS software, including visitation to national parks [13] and deforestation in Mexico [14].

With the use of agents, we diverge from a "one size fits all" approach to modeling farmers as economic optimizers. Instead, we mimic how different individuals respond to stimuli (e.g., incentives, regulation, information, and changing spatial structure of their neighborhoods) to produce land-use decisions. Further, the action of each individual "agent", and their interaction with one another (through agent communication or common environments), can result in unexpected behavior (i.e., produce emergent properties). By representing farmers as agents, this methodology attempts to capture the variety in their stimulus and response behavior in a real-world environment.

Because of the complex nature of human decision-making, we limited our modeling of human behavior to the probability of acceptance of CRP payments by individual farmers. To create an agent-based model of human decision-making behavior within the Cache River SDSS, we:

a. developed a typology of farmers based on observed behavior, and noted in the literature;

b. created stimulus-response models for each type of farmer;

c. spatially associated each farmer-type with land parcels within a watershed; and

d. modeled changes in behavior of certain "types of farmers" using a "diffusion of innovation" approach [14].

The typology of agents was based on research by Kraft et al. [11], who grouped farmers within the Cache River watershed into twenty categories on the basis of their attitudes towards the goals of survival, leisure, soil conservation, financial growth, expanded production and maintaining a rural life style. Each category is considered sufficiently homogeneous in their response to stimuli within a certain decision-environment set, and therefore can be represented by a single software agent. We used this categorization to create an initial set of farmer-agents.
Two different modeling approaches were used to build the actual agents: linear programming, and expert systems. Profit maximizing farmers were represented using the spatially-enhanced linear program described earlier, GEOLP. Individuals who are not profit maximizers were modeled through the use of expert system shells, where the range of possible farmer responses to stimuli (i.e., landuse decisions) were represented using IF-THEN rules. The rules are “mined” from existing survey and spatial data (e.g., soils, slope) using inductive learning algorithm (i.e., C5.0).

Next, the individual farmer agents were associated with spatially distributed parcels of land. The 2000 National Agricultural Statistical Service (NASS) Cropland Data Layer for Illinois containing statewide categorizations of agricultural activities, and farm data available from the local USDA/NRCS office, were used to develop a statistical model (using S-Plus) that predicts the association of farmer types with a farm based on physical farm parameters (e.g., soil type, farm size) and personal characteristics of a farmer (e.g., age, education level).

The introduction of CRP payments can be viewed as perturbations to a system that are communicated institutionally and personally between associated individuals [15, 16]. Adoption of CRP payments by agents was modeled as diffusion process resulting from the communication of individual experiences to neighbors with similar characteristics [17]. The rate of adoption, or rejection, of the CRP payment structure is moderated by a threshold value that reflects the cumulative experiences of individual farmers and their neighbors [18].

Finally, the system described above was used to simulate changes in the landscape arising from various levels of CRP payments. This simulation was primarily modeled within ArcView, with GEOLP and the expert-system shell being instantiated as necessary. Analysis of survey data obtained from the Cache River watershed was utilized to create individual agents.

Initial results obtained by running the agent-based models show deviation from the landscape generated by profit-maximization models. However, standardization of comparative measures is required before the results generated by the two approaches (economic-optimization versus agent-based) can be evaluated vis-a-vis one another.

5. Implications of the modelling technique for agrarian economies

We propose that the modelling techniques presented in this paper hold significant value for countries with largely agrarian economies (such as India) as well. While taking cropland out of production is a difficult (and politically untenable proposition) in the Indian context, it is possible that government subsidies to help farmers with technology to practice soil conservation measures can be targeted at farmlands that have a high rate of sediment loss. An SDSS similar to the one described above can be used to identify farmers with the most potential to improve water quality, and determine the level of economic losses incurred by them as a result of implementing the soil conservation measures. As with the U.S. scenario, payments made under a reimbursement program could be used to maximize reductions in sediment losses (thus retaining productivity of the soils and preventing excessive runoff) with no-net loss of agricultural croplands. It can be expected that such a program will significantly reduce Non-Point Source pollution, thereby improve the water quality of Indian rivers at the least possible cost.

6. Conclusions

Using a Spatial Decision Support System (SDSS), it is possible to identify a compensation strategy that can be used in agrarian watersheds to offset economic losses sustained by farmers as they attempt to reduce sediment erosion from farm fields. Further, the effectiveness of the compensation strategy, as measured in terms of acceptance by individuals in a watershed, can be modeled more realistically if strategies other than profit maximization are also considered during simulation. Using the SDSS, therefore, decision-makers can estimate the economic costs
(including monetary amounts and spatial distribution of the costs) associated with implementing a specific pollution prevention program in a watershed beforehand. This is particularly useful for agrarian economies, where it may be necessary to reduce intensive farming practices in certain watersheds in order to protect downstream water quality for human consumption and ecological preservation.

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8. References


9. Biographical Details

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