Ecological-Economic Modeling on a Watershed Basis: A Case Study of the Cache River of Southern Illinois

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Abstract:

A digitally represented watershed landscape (ARC/INFO GIS) is merged with farm optimization (linear programming) and sediment and chemical transport (AGNPS) models. Enhanced targeting of non-point source pollution to remedial policy and management initiatives result. The implications of which are linked back to farm income and forward to the managed ecosystem.

Introduction:

Watershed ecosystem management takes place on a landscape controlled by private landowners who operate farms or rent their land to other farm operators. In either case land use decisions will, in large part, reflect economic criteria like income maximization. Watershed ecosystem management plans how resources can be used to maintain or enhance ecological integrity. Conflicts with land users can occur if the ecosystem plan fails to reflect the economic uses to which the privately held land can be put. In watershed planning, methods are needed that link the landscape to private decision makers.

The Illinois' Cache River, a conservation priority watershed, has afforded the opportunity to model and examine these linkages between private land use decisions and watershed ecosystem management planning. An interdisciplinary effort has merged the digital representation of the Cache landscape (ARC/INFO GIS) with farm enterprise optimization (linear programming), and more recently, to sediment transport (AGNPS). This effort has the potential to result in enhanced targeting of non-point source pollution to suitable remedial policy initiatives or management practices. The implications of which can then be linked back to the income generating stream of private land uses and forward to the ecosystem under management. The effectiveness of this approach is demonstrated in the Big Creek subwatershed of the Cache River watershed. The Big Creek watershed can be decomposed into two distinct topographic regions. The upper watershed is characterized by moderate to steep slopes and supports a mixture land uses (pasture, forest and crop land). The lower section of the watershed, on the other hand, enters into the flat, heavily farmed flood plain of the Cache River.

Background:

The Cache River watershed located near the confluence of the Mississippi and Ohio Rivers encompasses 1,944 km^2 of five southern Illinois counties. The unique and diverse plant and animal communities have led to designating 58 sites as Natural Areas by the Illinois Dept. of Conservation, and two sites as National Natural Landmarks by the U. S. Dept. of Interior. More than 100 species of plants and animals on the Illinois threatened and endangered species list occur within the watershed. The landscape also supports a diversity of agricultural related enterprises with grain, cattle, and vegetable producing units most prominent.

Current threats to the Cache ecosystem, including the loss and fragmentation of natural habitats for plants, fish, and wildlife, dramatic alterations of the natural hydrologic regimes of stream systems and wetlands and excessive upland erosion and sediment deposition in wetlands are a direct result of agriculture. Other land use and economic activities are also incompatible with long-term maintenance of the ecology (Beck et al., 1993) Similar threats exist in most watersheds. However, as strategies are developed to enhance ecosystem quality, political and economic realities dictate a viable agricultural sector be maintained. The Cache watershed is located in an impoverished rural area with few linkages to surrounding regions and minimal infrastructure to support non-farm activity.

Studies have established that land-use changes associated with maintaining and enhancing the Cache watershed are not inherently detrimental to the local economy (Beck et al., 1995, Kraft, 1994). In these earlier studies, however, the linkages between land-use and ecological impacts were not well developed. Nor was adequate farmlevel data available to assess the impacts of proposed land-use changes on resource utilization and farm profitability. The work reviewed in this paper is the result of on-going interdisciplinary effort funded by the Nature Conservancy, the Illinois Water Resources Center, and the Illinois Council on Food and Agricultural Research

Data and Methods:

Critical to this effort is the accurate representation of soil structure by type, slope, and location along different reaches of Cache tributaries. Soil characteristics determine crop productivity, and to a large degree, farm income. Soil characteristics also determine the potential for sediment and chemical transport. ARC/INFO Geographic Information Systems(GIS) allowed for this accurate representation. Soils were digitized as a result of Nature Conservancy funding.

Special tabulations of the 1987 and 1992 Censuses of Agriculture on the returns from Cache River watershed farms resulted in land use statistics, in particular, farm size distributions (e.g., acres operated) and management resources (e.g. labor availability). These statistics, in turn, guided the development of farms modeled to maximize gross margin through linear programming(LP). Unique to the LP is the specification of multiple soil types differentiated by crop yields, and soil type erodability resulting from alternative cultural practices. Utilizing a clustering routine available in ARCINFO, the Big Creek landscape was allocated into 96 farming units with an average acreage of 245 acres (range of 56 to 716 acres). In 1992, the actual average Cache farm size was 256 acres.

In agriculture, users of linear programming can investigate, among other questions, how enterprises change with crop prices, how changes in labor availability affect enterprise selection, how changes in acreage will affect machinery needs and farm profits. More recently environmentally sensitive decisions have been incorporated in the linear programming framework. Taylor and Frohberg (1977) considered the economic impacts of banning herbicides and insecticides, and limiting nitrogen use in the US Corn Belt. Crowder et al. (1985) used linear programming to compare net returns, soil and chemical losses in runoff from alternative cropping practices. Bretas and Heath (1990) focused upon groundwater contamination. An existing representative farm linear programming model developed under grants from the Joyce Foundation (see Kraft and Toohill, 1984; Esseks et al. 1990), is modified to reflect the soil structure and farms of the Cache watershed.

The LP, in this analysis, allows corn, soybean, wheat, double crop soybean/wheat and alfalfa differentiated by tillage (conventional, conservation and no-till) and timing of crop activities. RKLS-factors from the universal soil loss equation (following Walker and Pope, 1983) were developed for each soil mapping unit. The LS-factor was developed based on average length and steepness of slope for respective soil types. The crop management factor, C, varied based on tillage operation, crop, and timing of tillage activity. For example the C factors for corn are estimated at 0.38 for conventional tillage fall-plowed, 0.18 for conservation tillage fall plow, and 0.05 for no-till. The conservation factor, P, was held constant at 0.85 across all soil types. Crop prices are simple average of monthly prices between 1992 and 1996(Illinois Grain and Livestock). Corn, soybean, wheat were priced at $2.60, $3.55 and $6.05 respectively. Alfalfa/hay at $80.00/ton. The Conservation Reserve Program (CRP) was an option. CRP rental rates were held equal to the average 1997 signup bid of $68.00 for the region.

Of the approximate 34,000 acres in Big Creek watershed, about 23,000 were deemed, based on Landsat images, suitable for cropping/haying/CRP activities. Table 1 presents the crop yields and selected soil loss characteristics for ten predominant Big Creek soil types. There were 90 distinct soil types mapped to the watershed. A review of this table demonstrates the wide diversity in soil productivity and erosiveness of particular soils. Within the watershed corn yields ranged from 125 bu/ac. on Wakeland Silt Loam (type 333) to 75 bu/ac. on the relatively steeper sloped and more erosive Hosmer Silt Loam (type 214C3 and 214D3). As indicated, an acre planted to corn given conservation tillage would result from 1.87tons/ac. to 37.05 tons/ac of annual soil loss. On some smaller farms there were less than five soil types, on larger farms in excess of fifteen types was common.

In total, the LP model considered over 900 cropping activities, differentiated by tillage and activity timing in maximizing gross margin, the return to the farmer's management and the capital invested in the business. Machinery availability reflected the equipment complement for corn-soybean farms os similar acreage. One full-time laborer was allowed for farms over 170 acres. One-half laborer on smaller farms. Estimated usage of the available labor and machinery (Doanes, 1996) was constrained based upon field days per time period (Illinois Agronomy Handbook, 1995-1996). Estimated costs were based on enterprise budgets for the southern Illinois region as prepared by the University of Illinois Extension Service.

The implications for farm income and soil loss were estimated for three scenarios; unconstrained individual soil type loss, soil type loss set at 2T and soil type loss set at 1T. Weakening the applicability of this, an intermediate result, is that the LP cannot estimate the dispersion of soils or chemicals to the creeks. The soil coverages generated by the LP, however, can serve as input to the Agricultural Nonpoint Source model (AGNPS).

AGNPS is an event based, distributed parameter model designed to model hydrology, erosion, and the transport of sediment and chemicals through a watershed. In the hydrology module, runoff volume and peak concentrated flow at the outlet of the watershed are calculated. The erosion module calculates total upland erosion and total channel erosion. Chemical transport is measured in terms of soluble and sediment-attached pollutants. Spatial heterogeneity and erosion, runoff, and sediment yield are calculated for each cell in the database which can then be aggregated to the watershed level. For demonstration purposes a single event, a one inch rain over a 6 hour period, was modeled. Computer programs were developed to construct a coupling between the ARC/INFO GIS, LP, and AGNPS. These programs allowed for the capture and manipulation of the spatial databases needed to parameterize and execute the LP and AGNPS programs.

Results:

Presented in Table 2 is the gross margin, soil loss(in total and as sediment yield), and tillage practices resulting from a scenario to optimize cropping decisions to maximize gross margin given no constraints on soil loss. Over $2.7 million in aggregate gross margin results in the unconstrained soil loss scenario. On average this is $28,482 per farm. As measured by the soil loss equation(RKLS derived soil loss) a “maximum” 204,076 tons of per annual soil loss (about 221% of T) results. A one-time 5- year rain event would result in 447 tons of sediment being discharged at the mouth of Big Creek. Neither conventional or no-till tillage practices entered the solution for corn or soybeans. Soybeans represented about 75% of watershed acres. CRP became the favorable alternative on 2,856 of the acreage.

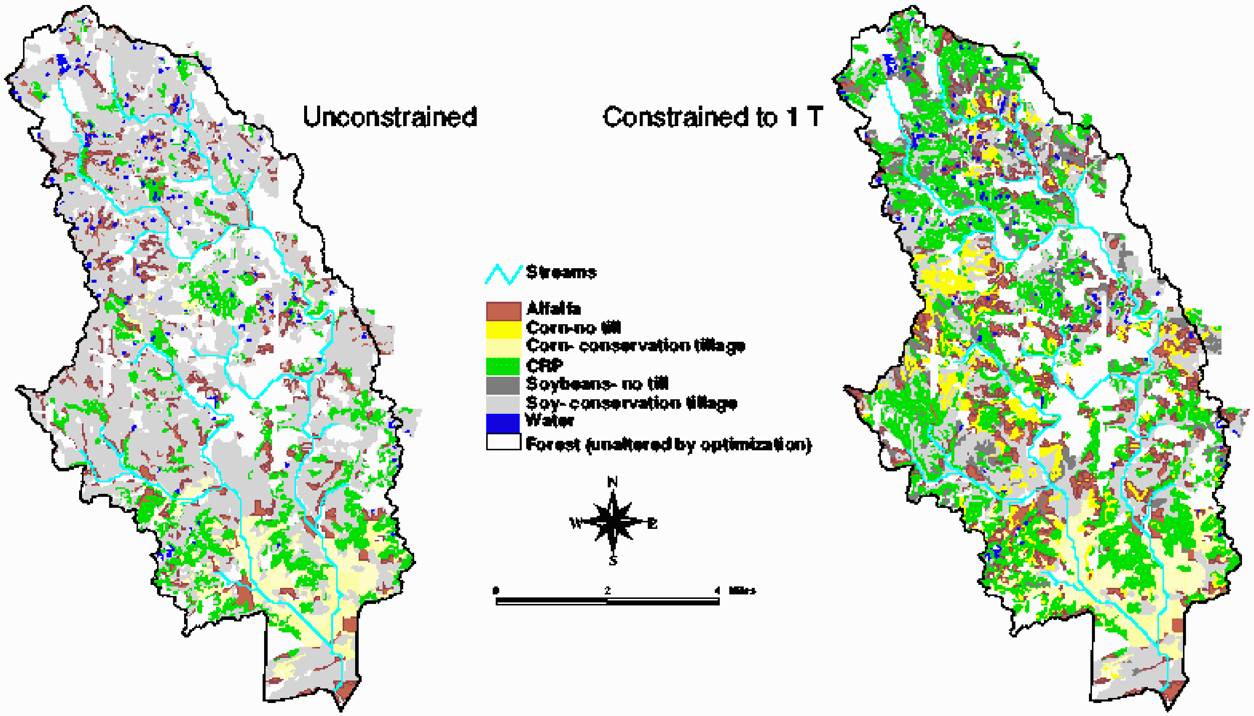
As soil loss constraints were tightened from “unconstrained” to 2T there was a modest reduction in gross margin but a significant reduction in soil loss. In Big Creek, gross margin fell from $28,482 to $28,135, on a per farm basis, with a corresponding reduction in soil loss in total of about 96,000 tons(a reduction of 47%). Aggregating across the watershed, gross margin fell by $33,000 or about $0.35 for each ton of soil loss reduced. The shift from 2T to T resulted in a larger proportional decrease in gross margin than the shift from “unconstrained” to 2T. Aggregated gross margin falls by about $75,000. An additional 41,000 tons of soil is saved. Or for each ton of soil loss reduced there was a $1.85 reduction in aggregate gross margin. In either case, on a per farm basis, the distributed cost would be quite small to achieve such soil loss reductions. Further work will determine if because of locational disadvantage some farms are forced to bear a greater proportion of the aggregated cost.

Soil discharge at the mouth of Big Creek is reduced by 131 tons, from 447 tons under the unconstrained solution to 316 in the 1T solution. This represents a decline of about 29%, much below the 67% reduction in soil loss as measured by the soil loss equation. Indeed, if measured as above, each ton removed from the streams cost about $824.00 in reduced aggregate gross margin, or about $9.00/ton per farm.

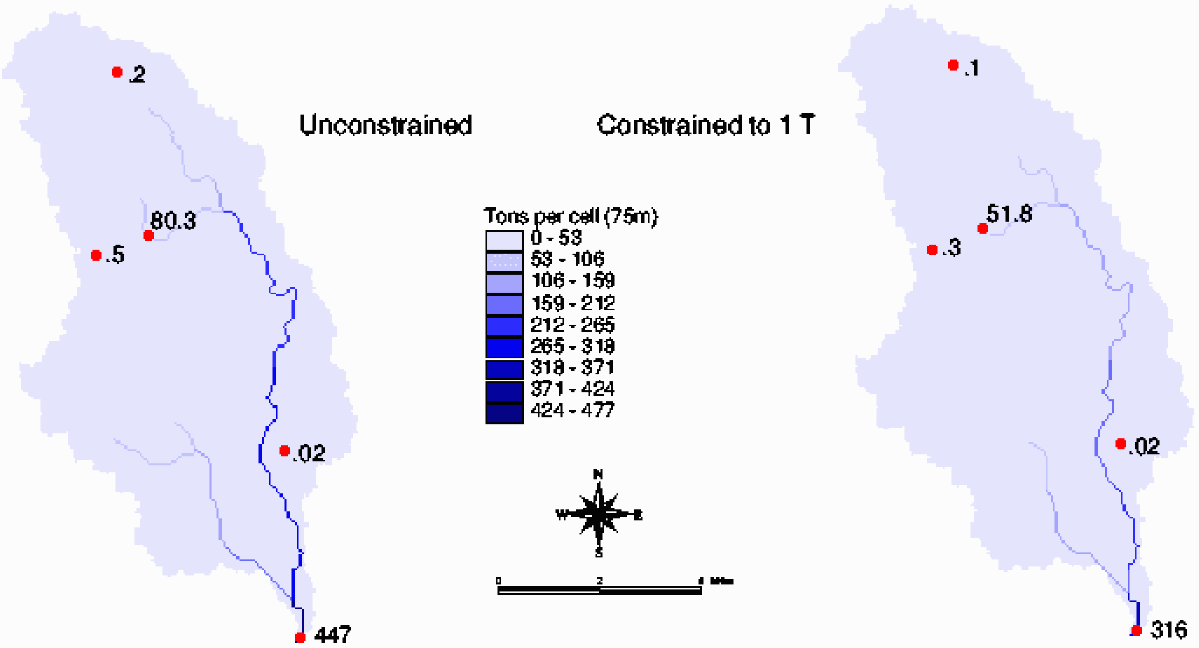
Figure 1 presents a land use mapping of the watershed. The left map represents the land use pattern as determined in the unconstrained solution. The right map when soil type loss is constrained to 1T. In both maps, the white areas within the watershed boundary reflect forested and other use areas unavailable for farming. It is apparent that to meet a 1T soil loss constraint, no-till farming practices and increased land retirement through the CRP would be required. In the 1T solution no-till is now practiced upon 25% of the combined corn and soybean acreage, up from zero no-till in the unconstrained solution. CRP acreage has grown to about 27% of the watershed acreage, up from about 12%.

Figure 2 presents an interesting look at the soil discharge as calculated from selected cells

Land Use Pattern



Sediment Yield



by AGNPS. Again, the unconstrained and 1T solutions are compared. The most striking feature is the disparity between in-stream and land based readings. Or alternatively, the contribution to sediment yield by each producer is quite small, but in aggregate as measured at critical junctures, ie. the mouth of Big Creek, the individual minor contributions can have a measurable impact.

Discussion:

In review, this linkage of modeling techniques would seem to hold promise. In particular, the interplay between managerial decision making and location can be better determined and critical watershed areas can be located for remedial attention. This work, is however, very much a work in progress. For example, producers do not solely base their acreage decisions on soil series mapping units. Producers farm fields. To produce a more realistic representation of the landscape of Big Creek watershed the results produced by this technique must be generalized to the field level. In Southern Illinois, pest management is a crucial part of the acreage decision. The soybean/corn ratio as depicted in these initial solution is, therefore, unlikely. This base scenario, as well as a filter stripping scenario, are in development.

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Table 1. Representative Soils, Crop Yields and Soil Loss Characteristics for Big Creek Farms

	Crop Yield						soil loss per planted acre(in tons/ac)			
Soil Type	Corn	Soybean	Wheat	Alfalfa (tons/ac)	T-Value	RKLS	conservation corn	no-till corn	conservation soybean	no-till soybean
333	125	44	50	4.1	5.00	10.38	1.87	0.52	1.66	0.62
308D3	105	37	42	3.4	4.00	177.13	31.88	8.86	28.34	10.63
308C2	110	38	44	3.6	5.00	99.63	17.93	4.98	15.94	5.98
308B2	120	42	48	4.0	5.00	36.67	6.60	1.83	5.87	2.20
214D3	75	26	27	2.5	3.00	205.86	37.05	10.29	32.94	12.35
108	107	35	44	3.8	5.00	12.06	2.17	0.60	1.93	0.72
214B	105	37	47	3.4	4.00	37.79	6.80	1.89	6.05	2.27
308E3.				3.0	4.00	199.27				11.96
214C3	75	26	34	2.5	3.00	94.08	16.93	4.70	15.05	5.64
5308D	85	33	38	2.8	5.00	44.32	7.98	2.22	7.09	2.66

Table 2. Gross Margin, Soil Loss and Crop Acreage Resulting from Soil Loss Scenarios

	Unconstrained	2T	T
Gross Margin			
watershed(mil)	$2.734	$2.701	$2.626
average/farm($)	$28,482	$28,135	$27,370
Soil Loss			
total(tons/acre)	204,076	108,183	67,447
%T	220.9%	112.7%	68.8%
sediment yield(tons/cell)	447	371	316
Tillage Practices			
crop acreage(corn)			
Conservation	2,136	2,168	4,144
No-Till	0	230	2,179
crop acreage(soybean)			
Conservation	15,003	13,153	9,576
No-Tillage	0	3,205	2,491
Alfalfa/Hay	2,974	3,227	3,318
CRP	2,856	4,593	6,130

Note: Sediment yield is measured as tons in a 75 square meter cell.