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Application of SWAT in the evaluation of salmon habitat remediation policy[†]

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Abstract:

Agricultural non-point source water pollutants such as sediment, pesticides and nutrients have been identified as contributing to the environmental distress of salmon runs in the Pacific Northwest. Policies to control non-point pollution from agricultural production can be classified as command and control or economic incentive policies. In application of a command and control policy, a regulator (usually a government agency) mandates a reduction in emissions or limits an agricultural production activity. Examples are a mandated reduction in nutrient application, or a reduction in emission of a nutrient to streams. Economic incentive policies are designed to achieve the same level of pollution control, while allowing some flexibility in maximizing profit.

A tax on inputs is one frequently cited incentive measure. In this study, alternative policies to reduce non-point emissions from agriculture on the Columbia Plateau of Washington, Oregon and Idaho are evaluated. The environmental efficiency and effects on profits by reduction of nitrogen from fertilizer under command and control regulation and tax incentives are compared. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS SWAT; environmental policy; data envelopment analysis

INTRODUCTION

The Pacific Northwest of the United States has long been known for large salmon runs. In recent years the runs have declined to the point where several salmonid species are listed as threatened or endangered under the Endangered Species Act. This act requires that habitat be improved to preserve the endangered salmonids, and provides legal machinery to force environmental remediation. Agricultural producers have been identified as one source of habitat degradation, primarily through non-point source pollution from sediment and agricultural chemicals (Pacific Fisheries Management Council, 1999).

The Soil and Water Assessment Tool (SWAT) is 'a river basin, or watershed, scale model developed by Dr Jeff Arnold for the USDA Agricultural Research Service (ARS). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time' (Neitsch *et al.*, 2001a). The scale of SWAT provides a way of analysing the physical variables involved in habitat remediation in a very large area.

It is not sufficient to model only the physical effects of habitat remediation policies. The success (or failure) of any policy will ultimately depend upon human behaviour; in this case, the behaviour of agriculture producers. It is necessary to include the financial effects of policy with the physical effects when assessing a proposed policy. In the past, economic analysis of production has only included physical processes in a general way, if at all. On the other hand, SWAT does not include any economic behaviour. In effect, people

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and their choices are exogenous to SWAT. The goal of this study was to link human behaviour (economics) to SWAT in order to analyse environmental policy.

INTEGRATION OF SWAT WITH ECONOMIC MODELS

Earlier integrated model studies

Srinivasan and Arnold (1994) categorize physical process models using three criteria: (a) non-spatially distributed or spatially distributed (e.g., areas with different physical characteristics can be modelled simultaneously with physical links, such as streams, among them); (b) single event or continuous time; and (c) field scale or watershed/basin-wide. Spatially distributed, continuous time, watershed/basin-wide models are the most general, and therefore the most useful category of model for regional or national analysis of policy. The data for this type of model are usually aggregated at the watershed level based on densely sampled grids (e.g. raster maps). However, very little economic data is collected on a watershed or grid basis. In this paper, we present a methodology to link data sets and models at any watershed or grid level of aggregation.

Many previous studies linking biophysical and economic models use field-scale models such as EPIC (Williams *et al*., 1990). The most common strategy in these studies is to construct a 'representative farm' based on cross-tabulated physical data on soil texture, slope, precipitation and crops. For example, a representative farm might be 200 acres growing pasture on sandy loam with a slope of 1%. The corresponding data needed for economic modelling of the representative farm, chiefly input and output prices and quantities, have been obtained using a variety of methods. Some examples include the use of extension service budgets (McCarl *et al*., 1999), state (Huang *et al*., 1996) or regional (Taylor *et al*., 1992; Mapp *et al*., 1994) estimates of production budgets, and estimated production functions based on a physical model with regional prices (Johnson *et al*., 1991; Larson *et al*., 1996). The spatially distributed, continuous time, watershed/basin-wide model SWAT (Arnold *et al*., 1994) has been linked to economic behaviour using a budget generator to produce the required data for each watershed analysed (Qiu and Prato, 1999).

The SWAT model contains representations of many physical processes, but requires human intervention to select parameters. For evaluation of policy, the parameters associated with agricultural practices are particularly relevant. Consider the analysis of nutrient application. In the simplest case, the human running SWAT will choose different levels of fertilizer application. These choices will be based on different scenarios derived from enterprise budgets (Prato *et al*., 1996), surveys of actual practice, legislative goals, or any number of considerations that a farm operator or policy-maker might use in the application decision. The approach taken in this study is to model a farm operator, and link the farm operator model to SWAT in such a way that this model chooses the parameters for SWAT in response to policies imposed by some administrative unit of the state.

Data envelopment analysis

In order to model the behaviour of a farm operator, it was assumed that the operator had a single goal, to maximize profits. The task is then to specify a model that adequately represents the technology which the operator uses, and optimize profits given that technology. The class of models selected for use in this study is based on using a linear program to calculate the maximum output possible using a particular technology. This calculation establishes a production frontier, which can used with input and output prices to calculate the maximum profit attainable by a producer. The method in effect constructs a linear piecewise bound over the data, and is generally referred to as data envelopment analysis (DEA) (see Färe *et al*., 1985, 1994 for more details).

More formally, in a data set there are $k = 1, \ldots, K$ observations of farms. Each farm uses $x = (x_1, \ldots, X_M) \in \Re^M_+$ inputs to produce $u = (u_1, \ldots, u_N) \in \Re^N_+$ outputs. The observed inputs $x^k = (x^k, \ldots, x^k_M)$ and the observed outputs $u^k = (u^k_1, \ldots, u^k_N)$ are used together with the intensity variables $z^k \geq 0, k = 1, \ldots, K$, to form the reference technologies. Here we do not constrain the farms with respect to their profit, i.e., profit may be positive or negative. This condition may be modelled by constraining the intensity variables to sum up to one. Our basic model is then

$$T = \left\{ (x, u) : u_n \le \sum_{k=1}^{K} z^k u_n^k, \qquad n = 1, \ldots, N \right. \tag{1a}$$

$$x_m \ge \sum_{k=1}^{K} z^k x_m^k, \qquad n = 1, \ldots, M \tag{1b}$$

$$\left. \sum_{k=1}^{K} z_k = 1, \qquad z_n \ge 0 \right\} \tag{1c}$$

Denote input prices by $p^k \in \Re_+^M$ and output prices by $r^k \in \Re_+^N$. Then the profit of farm k can be computed as the solution to the following linear programming problem:

$$\pi(r^k, p^k) = \max \sum_{n=1}^{N} r_n^k u_n - \sum_{m=1}^{M} p_m^k x_m \tag{2a}$$

$$\text{s.t.} \quad \sum_{k=1}^{K} z^k u_n^k \ge u_n, \qquad n = 1, \ldots, N \tag{2b}$$

$$\sum_{k=1}^{K} z^k x_m^k \le x_m, \qquad m = 1, \ldots, M \tag{2c}$$

$$\sum_{k=1}^{K} z^k = 1 \tag{2d}$$

$$z_k \ge 0, \qquad k = 1, \ldots, K \tag{2e}$$

Policy constraints

Salmon remediation policy in the Northwest United States is primarily concerned with water quality. In particular, nutrients and sediment from agricultural activities are seen as damaging to salmon and salmon habitat (Pacific Fisheries Management Council, 1999).

Major policy instruments for controlling agricultural non-point source pollutants generally fall into two categories. Command and control policies, such as an upper limit on chemical use or a restriction on management practices, make up one category of policy. The second category includes economic incentive policies. These may include pollution permit trading, 'green taxes' on inputs, and cost sharing between government and producers on implementation of environmentally beneficial management practices. To demonstrate the use of SWAT in analysis of alternative policies, a command and control policy and an input ('green') tax were selected for comparison.

Nitrogen fertilizer entering streams is considered to present a hazard to salmon. In particular, nutrient loading is thought to be responsible for 'increased primary and secondary production, possible oxygen depletion during extreme algal blooms, lower survival and productivity, increased eutrophication rate of standing waters, certain nutrients (e.g., non-ionized ammonia, some metals) possibly toxic to eggs and juveniles at high concentrations' (Pacific Fisheries Management Council, 1999). One method to deal with nutrient loading from agricultural application of nitrogen is to restrict the amount which may be applied, a simple command and control policy.

In this case the model (2) will be changed to reflect the quantity restrictions, and the technology is the following (fertilizer is defined as input M, the restricted input):

$$T(c_m) = \left\{ \begin{aligned} (x, u) : u_n &\le \sum_{k=1}^{K} z^k u_n^k, \qquad n = 1, \ldots, N && \text{(3a)} \\ x_m &\le \sum_{k=1}^{K} z^k x_m^k, \qquad m = 1, \ldots, M-1 && \text{(3b)} \\ C_M &\le \sum_{k=1}^{K} z^k x_M^k && \text{(3c)} \\ C_M &= c_M \text{ acres}_k && \text{(3d)} \\ \sum_{k=1}^{K} z_k &\le 1 && \text{(3e)} \end{aligned} \right\}$$

where c_M is the per acre restriction of the Mth input and acres_k is the number of acres to which the Mth input is applied by the kth farm.

One of the simplest approaches to nutrient application control through economic incentive is a tax on the purchase of nutrients. This type of incentive is attractive because it is relatively inexpensive to implement and monitor. Some of these so-called 'green taxes' have been implemented, and experience is accumulating in their use (Brännland and Gren, 1999). To apply an input tax on the Mth input (fertilizer), the objective function (1) becomes

$$\pi(r, p, tax) = \max \sum_{n=1}^{N} r_n u_n - \sum_{m=1}^{M-1} p_m x_m - x_M(p_M + tax) \tag{4}$$

where tax is the tax rate. Taxes on multiple inputs are represented by additional terms in the objective function, and the profit maximization problem with taxes is

$$\pi(r, p, tax) = \max \sum_{n=1}^{N} r_n u_n - \sum_{m=1}^{M-1} p_m x_m - x_M(p_M + tax) \tag{5}$$
$$\text{s.t.} \quad (x, u) \in T$$

Many more complicated environmental remediation schemes may be represented by adding additional constraints. The two alternatives presented here show the important features of the basic model specification. In the application of this model, the amount of inputs that will maximize profits are chosen by maximizing profit under policy constraints. These amounts are then used in SWAT to assess the environmental efficiency of the policy under consideration.

Links to SWAT

The two policy examples above both relate to reduction of nutrient application. The economic model specified there is used to calculate the amount of nutrient that will maximize profits under the example policies. The critical piece of the analysis which SWAT provides are estimates of the environmental effects of the different policies. In principle, SWAT is relatively simple to integrate with the economic model. One simply takes the optimized choice variables from the DEA model and uses them as inputs to SWAT. It is a critical concept that the inputs to SWAT are taken from the constrained optimization. Inputs to SWAT from other sources will not reflect policies and prices facing a producer; in effect there are no people in the model without this output/input link between economic and physical models.

With the large array of input and management variables that it contains, the optimum inputs chosen by the economic model are easily substituted as management inputs to SWAT. For the two agricultural non-point nutrient reduction policy examples above, fertilizer application from the final optimization is substituted in the management file for each sub-basin. A FORTRAN program was used to rewrite the management files (.mgt) with values calculated in the DEA analysis.

The key linkage between an economic model and SWAT is to force SWAT to produce the output (yield) calculated from the economic model. This yield, in effect, represents all the trade-offs among input prices, output prices, the available technology and policy restrictions. In SWAT management files (.mgt) the yield can be controlled through the use of the biomass override variables BIO_TARG and HITAR. BIO_TARG (biomass target) specifies the total biomass that the plant will produce each year. SWAT then adjusts the daily increment of biomass change to match the specification using the following equation (Neitsch *et al.*, 2001a):

$$\Delta bio_{act} = \Delta bio_i \cdot \frac{(bio_{trg} - bio_{i-1})}{bio_{trg}}$$

where Δbio_{act} is the actual increase in biomass on day i, Δbio_i is the SWAT calculated potential biomass increase on day i, bio_{trg} is the user-specified total biomass at harvest, and bio_{i-1} is the accumulated biomass on day $i - 1$.

The variable HITAR allows the user to specify the harvest index target, where the harvest index is defined to be 'the fraction of the above-ground plant dry biomass removed as dry economic yield' (Neitsch *et al.*, 2001a). The relation of harvest index and biomass at harvest is known for many plants. It is therefore a simple matter to calculate the variables HITAR and BIO_TARG necessary to force SWAT to simulate the yields calculated from the economic model.

SWAT users are warned (Neitsch *et al.*, 2001b) that the use of HITAR and BIO_TARG is not appropriate where 'you are studying the effect of management practices on yields or you want the biomass to vary in response to different weather conditions'. Where the SWAT model is used alone, this is true. In this study, the use of SWAT with DEA models in fact allows the study of the effect of management practices on yields in a much richer way than is possible with either model alone, since the economic factors driving those practices are explicitly considered.

APPLICATION TO COLUMBIA PLATEAU

The Columbia Plateau forms the largest hydrologic unit in the Pacific Northwest. The area supports a large proportion of the agricultural production of the Pacific Northwest, and the effects of this production on salmon habitat continue to be of concern to many stakeholders. There is a large acreage of wheat and barley production on the plateau. This production lends itself to less complicated modelling because there are a small number of inputs to production, and an annual harvest operation (i.e., it is not necessary to model a multi-year production cycle). Therefore farms on the Columbia Plateau with wheat or barley or both, but with no cattle, were chosen as the production technology for this study.

Physical data

From the US Geological Survey (USGS), digital elevation models (DEMs, records of terrain elevations for ground positions at regularly spaced horizontal intervals), hydrologic unit maps of the United States (which show the boundaries of river basins) and land use/land cover raster maps were used as the primary inputs to SWAT.

Soil data for input to SWAT was taken from the STATSGO data set. STATSGO is a digital general soil association map developed by the National Cooperative Soil Survey and distributed by the Natural Resources

Conservation Service, USDA on their website. It consists of a broad-based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape.

Economic data

Economic data on farm operation was obtained from the 1994 Farm Costs and Returns Survey (FCRS), a survey jointly administered by the National Agricultural Statistics Service (NASS) and the Economic Research Service (ERS) in the US Department of Agriculture. The FCRS sample is drawn without replacement from stratified area and list frames of farm operations. Several thousand usable questionnaires with over 300 variables are received each year. The variables used in this study included yields, acres harvested and quantities used of labour, machinery, seed, gas and oil, insurance and fertilizer. Where expenditures were not available, state-level prices from NASS price summaries were used.

Modelling procedure

As specified above, a command and control policy was modelled and compared with an economic incentive policy. In economic theory, the best environmental policy is to set the marginal cost of pollution abatement equal to the marginal social value of pollution abatement. This 'first best' policy is difficult to specify, not least because there is no consensus on measurement of social value. In addition, monitoring of non-point source pollution would be required for each producer. A tax on an input or on the emissions is a commonly discussed 'second best' policy for pollution abatement. A tax on an input has much lower transaction costs in its application than an emissions tax, since no monitoring is required. The input tax was chosen for this study as one of the most practicable economic incentive policies to be considered as an alternative to a command and control policy.

The demand for nitrogen fertilizer is inelastic, and a 300% tax was required before every farm in the sample reduced fertilizer application. 'Inelastic' in the economic sense means that a small change in the rate of fertilizer application has a large effect on crop yields, and a farmer is therefore able to pay a high price

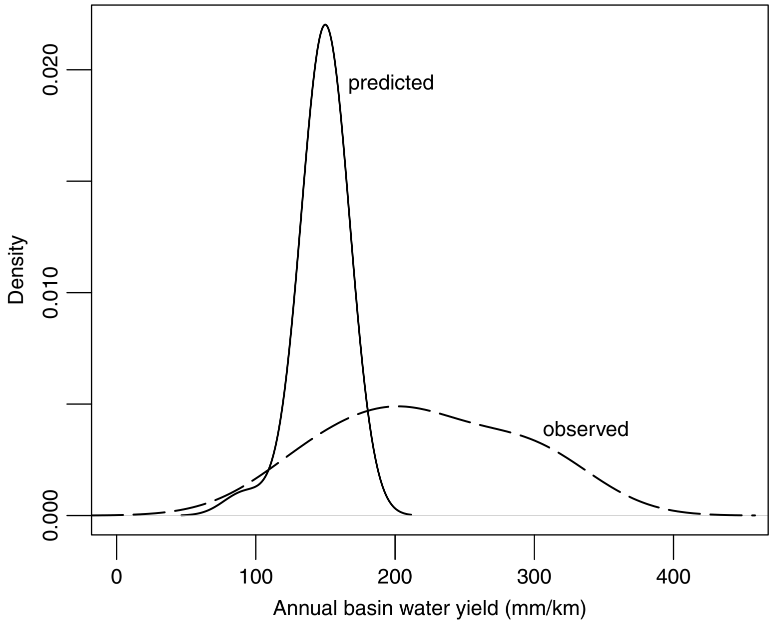

Figure 1. Comparison of estimated probability density functions of observed annual water yield (dashed line) for the entire basin with predicted water yield using SWAT

to keep yields up. The observation of inelastic demand is consistent with groundwater studies cited above, where the minimum nitrogen tax considered was 100%. The command and control policy analysed was a 25% reduction in nitrogen fertilizer enforced on each producer. The input tax policy was a 300% tax on nitrogen fertilizer. These policies are approximately equivalent in that this level of taxation on nitrogen fertilizer resulted in an approximately 25% reduction in total nitrogen fertilizer application. The policy difference is that under the tax plan a producer may continue to fertilize at any level which maximizes profit, while there is no choice of the level of fertilizer application under the command and control policy.

The DEA model was specified and solved using the generalized algebraic modelling system (Brooke *et al.*, 1998), and the physical modelling was done with SWAT version 98·2 under the Solaris operating system. Three separate runs of the combined models were required. The first established a basis for comparison by calculating the maximum profit and the environmental effects of production with no restriction on nitrogen fertilizer application. The second was an implementation of Equations (3), the command and control policy. The third implemented the green tax on an input, Equation (4).

RESULTS AND DISCUSSION

No calibration of SWAT for the study was carried out. The most basic calibration of SWAT adjusts the predicted annual water yields to approximate observed water yields. In order to check if SWAT predicted the water yield without calibration, the observed annual water yield at the mouth of the watershed was compared

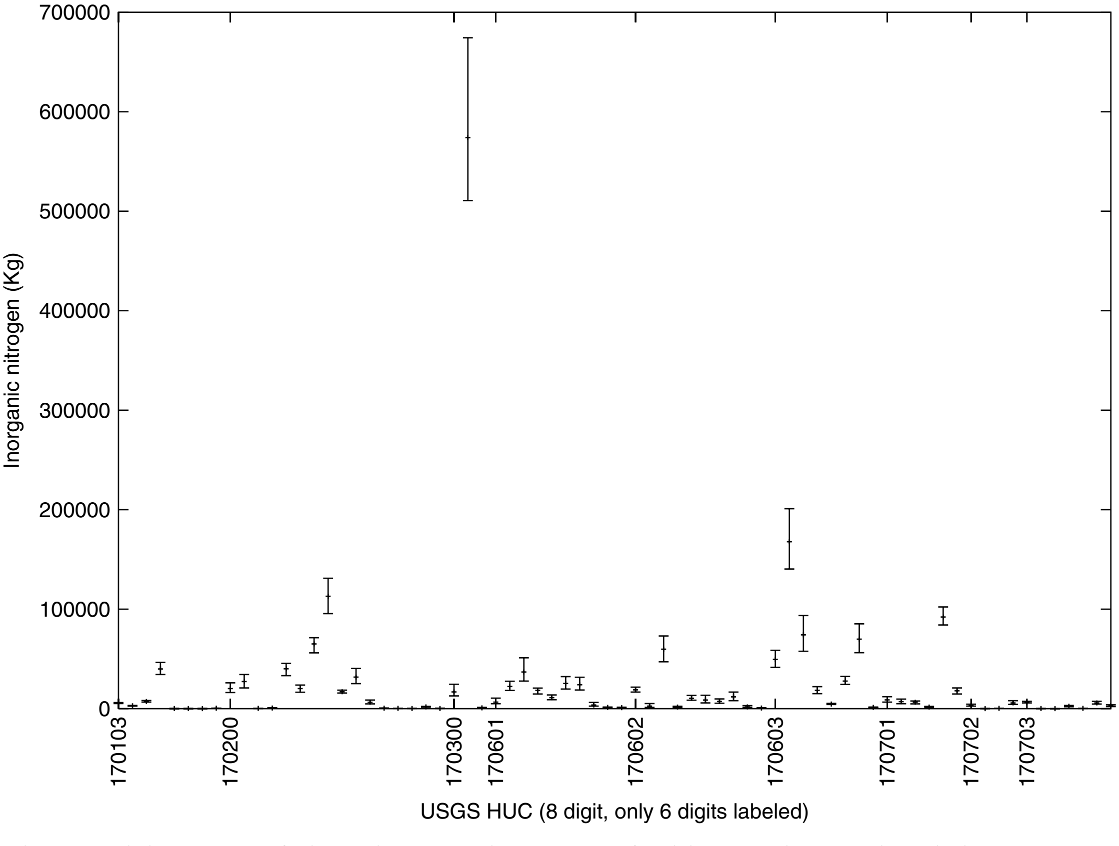

Figure 2. Variation and level of mineral nitrogen reaching the mouth of 8-digit hydrologic cataloguing units in the study area

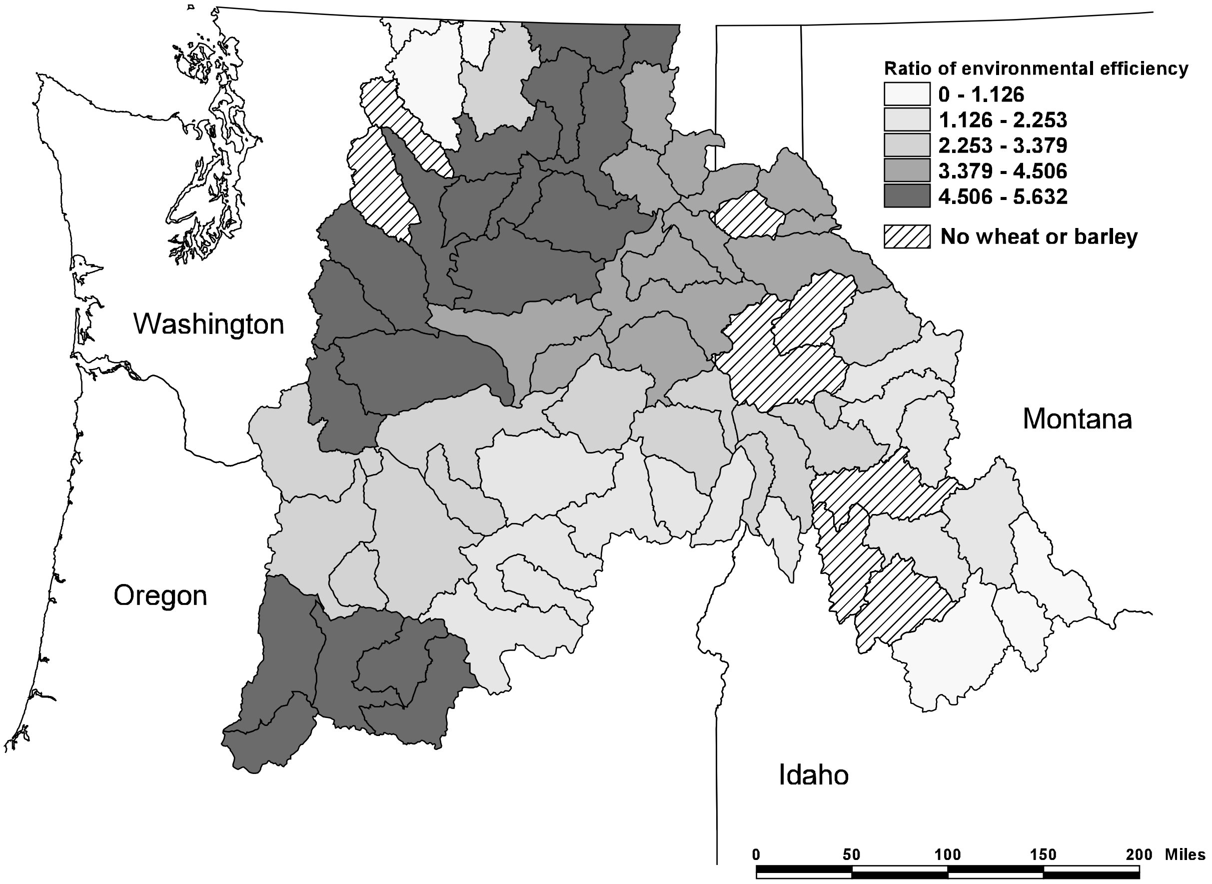

Figure 3. Ratio of environmental efficiency of a tax incentive policy to a command and control policy for reduction of non-point pollution from nitrogen fertilizer

with predictions from SWAT. The observed water yield was calculated from daily mean flow data collected by the USGS at the Columbia River at The Dalles, OR (USGS 14105700), the Columbia River at the International Boundary (USGS 12399500), the Snake River at Hells Canyon dam, ID–OR state line (USGS 13290450), and the Okanogan River at Oroville, WA (USGS 12439500). The probability density function of the observed water yield was calculated from the distribution of average daily flows (1965–1999) at USGS 14105700 less the flows at USGS 12399500, USGS 13290450 and USGS 12439500. Estimates of the probability density functions of observed and predicted values were calculated using a kernel density estimator (Scott, 1992), and are shown in Figure 1. Confidence intervals for the difference in means of the observed and predicted water yields were calculated using the bootstrap-*t* approach with 1000 draws (Efron and Tibshirani, 1993). The observed difference in means, 72 mm, is within the 95% confidence intervals of 74·2 and 48·6. Although the null hypothesis of equality of means cannot be rejected, the variances and shape of the distribution of the predicted and observed water yields are clearly different. This calculation leads to the conclusion that the mean values of a number of SWAT runs will adequately model water yield in the basin, but the variance will be underestimated.

There is a very large amount of information produced by the combination of models specified above. The DEA model results include the optimal level of all inputs, outputs and profit, while the SWAT model produces values for dozens of physical values at the watershed level. For the policy study discussed here, only the maximum profits, optimum level of fertilizer application, and level of inorganic nitrogen transported by surface water reaching the mouth of the watershed (*NSURQ*) were required.

The DEA model is deterministic, and so variation is not calculated for the values which result from the optimization solution. For this reason, variation of maximum profit and the optimal level of fertilizer application are not available. The variation of *NSURQ* can be estimated from multiple SWAT runs. For this purpose, 20 SWAT runs using historical weather provided the data, and confidence intervals for *NSURQ* were estimated for each sub-basin using the bootstrap-*t* approach with 1000 draws (Efron and Tibshirani, 1993). Error bars at the 95% confidence interval about the mean for each subwatershed (USGS 8-digit HUCs) are displayed in Figure 2. The mode of each distribution was used in the policy comparison.

To compare policies, a measure of environmental efficiency of a given policy was defined as the change in profit divided by the change in *NSURQ*. This measure gives the dollar amount that a producer has to give up to reduce the amount of N released into a reach by 1 kg/ha. To visualize the result, the ratio of environmental efficiency of the tax policy to the command and control policy was calculated for each watershed in the study area (Figure 3).

The main result of the comparison of a command and control policy with a tax incentive policy is that the tax incentive policy is generally more efficient in achieving reduction of emissions. While the command and control policy provides approximately the same result in a few watersheds, it is more costly in the large majority of watersheds: up to 5·6 times the cost of the tax incentive policy in some regions. This result is consistent with theoretical analysis and actual observation of tax incentive policy (Brännland and Gren, 1999).

Figure 3 shows clearly that the environmental policies examined here must be specified at the watershed level. The effect of each policy is highly variable across watersheds. A decision-maker would have to take account of this variation in designing an efficient policy mechanism for environmental remediation.

CONCLUSION

The combination of SWAT and DEA models gives results that indicate if a policy should be specified at the watershed level or whether a single policy is efficient. The method presented also enables estimates of the financial and environmental effects of alternative policies. A direct link between SWAT and an economic model provides a great deal more information than either model alone. The combination of SWAT with an economic model is very useful, and offers a large scope for environmental policy analysis.

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