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Agriculture, Ecosystems and Environment 104 (2004) 159–170
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Conducting economic policy analysis at a landscape scale: examples from a Philippine watershed

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Abstract

Given the strong and growing policy concern about high rates of hillside erosion and downstream sedimentation associated with upland agriculture, there is a need for analytical tools that can be easily used by researchers and environmental managers at several levels. In order to help meet this need, this paper presents an approach to policy modeling that emphasizes links between economic policy changes and environmental outcomes at a landscape scale. Stylized farm models are used to predict changes in household land allocation arising from agricultural policy changes, with explicit incorporation of biophysical feedback from erosion outcomes to agricultural productivity and subsequent crop choices made by optimizing farmers. Outcomes are combined to predict aggregate economic and environmental impacts. The method is applied to data from the Manupali watershed in the Philippine province of Bukidnon. Simulation results show how input and output pricing policies can have deleterious effects on the environment, but also show that in some cases policies that appear detrimental to producers—such as a modest tax on production of highly erosive crops—can produce welfare gains by discouraging patterns of land use that are unsustainable in the long run. The paper concludes that such analyses can help those involved with watershed management, from policy makers to local institutions, by focusing attention on key issues and trade-offs.

Keywords: Land use; Erosion; Philippines; Simulations; Watersheds; Agricultural tax policy

1. Introduction

High rates of hillside erosion and downstream sedimentation are among the most important agricultural externalities in the developing world (Anderson and Thampapillai, 1990; World Bank, 1992). Suspended solids reduce the quality of water for human consumption (Munasinghe, 1992). Silting of streams increases the risk of flash floods (UNESCO, 1982). Accumulation of silt in coastal habitats reduces productivity of aquatic ecosystems (OECD, 1993). And accumulation of sediment in reservoirs reduces hydroelectric power generation capacity and accelerates wear on turbines and power generating equipment (Naiman, 1995). Of additional concern is that erosion from upland farming creates sediment in downstream irrigation systems, reducing both their productivity and expected life (e.g. Cruz et al., 1988; DuBois, 1990). This is especially important in light of evidence that shortages of reliable water supplies preclude expansion and intensification of agriculture in many low-income areas of Asia (Myers, 1988; Svendson and Rosegrant, 1994). As an example, recent estimates from the Philippines suggest that between 74

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doi:10.1016/j.agee.2004.01.014

and 81 million t of soil are lost annually, and that between 63 and 77% of the country's total land area is affected by erosion (FMB, 1998). Sedimentation has reduced storage capacity at all of the Philippines' major reservoirs, and has measurably affected domestic water consumption, power generation, and irrigation; furthermore, over the last 25 years dry season irrigated area has fallen by 20–30% in several of the country's key irrigation systems (FMB, 1998).

In response to these and other environmental concerns, watershed protection and management has become a policy imperative in the Philippines, as in most of the densely populated regions of South and Southeast Asia (Doolette and Mcgrath, 1990; APO, 1995). As a result, the role of policy analysis as a precursor to policy making has expanded, and with it the need for rigorous yet easily implemented tools that can be used by researchers and those charged with environmental management at various levels. In this paper we discuss the design and use of such a tool. Our unit of analysis is the farm household, and we calculate outcomes using land-use data at a watershed scale. The model integrates various strands of multidisciplinary natural resources research so as to assist with the evaluation of policy changes that affect agricultural land management. Our modeling goal is to provide researchers and policy makers with an opportunity to easily conduct "what if"? exercises focusing on the potential impacts of agricultural policy changes. Rather than aim for the exact measurement and estimation of watershed processes, we instead seek to highlight potential signs and magnitudes of changes arising from shifts in policies. In addition to capturing core interrelationships of biological and economic phenomena, our modeling strategy addresses the need to assess potential budgetary and human welfare implications of induced changes in land use at the watershed scale.

2. Methods and data

2.1. Overview

In a recent review of simulation modeling for watershed management, Westervelt (2001) outlines a broad set of perspectives regarding landscape-scale modeling and simulation. We build on and extend the approach taken in models that predict watershed-scale changes—whether complex process-oriented models such as EPIC and GLEAMS (e.g. Williams, 1995; Leonard et al., 1987), computationally intensive cell-based models (e.g. Costanza and Maxwell, 1991), or aggregated plot models, such as that used here—to evaluate potential impacts of policy changes. A key difference in our work is that—by contrast with the foregoing classes of model—we allow for changes in economic incentives to influence on-farm optimization decisions. These decisions, in turn, produce changes in environmental variables. We use empirical data to parameterize stylized models of agricultural land use, calibrate the model to reflect existing land use patterns, and then use the model to predict changes that might result from shifts in policy. We depict the watershed as a set of spatially distinct agents and resource stocks that together characterize essential features of the local landscape and economy. Agents and resource stocks are linked both spatially and temporally through cause and effect and feedback mechanisms. In developing the model we draw upon empirical research on smallholder decision making (e.g. Coxhead et al., 2001). Decisions in the model are influenced by the interplay of wages, prices, and economic opportunities in the general economy, and the structure of our model incorporates a number of points of entry from the policy realm.

2.2. Model

The model consists of four similar, but distinct, representative households and contains three connected sectors: (1) an optimizing upland farm sector consisting of four representative farm households, each growing a set of upland crops; (2) a policy sector consisting of policy parameters that influence economic incentives faced by farmers; (3) a lowland (public) sector that is affected by externalities generated upstream and the budgetary implications of policy changes. The model is designed to simulate physical effects (such as erosion) that flow from the upland agricultural sector to the lowland sector. Main stock variables in the model include soil and sediment. The former is measured at the farm level and the latter is measured at a stylized receptor site. Each stock variable is assigned an initial value that evolves according to an endogenously determined trajectory of land use.

Outcomes in the model reflect the resource allocation decisions of representative upland farms. These choices are influenced by relative prices (and by policies such as taxes or subsidies on crops), the relative risks of the crops (measured by a variance–covariance matrix for prices), yields, input costs, access to credit, and risk aversion. The flow of erosion from upland farms—mitigated by sediment delay and governed by zone-based transfer coefficients—determines the rate of sediment accumulation in the lowlands. Farm-specific erosion rates depend on crop shares, area planted, rainfall, and slope. Our motivation for studying erosion and sediment comes from a study of lowland farms in the Manupali watershed that indicated negative impacts from sediment on area planted to rice (Singh et al., undated). It should be noted that although more sophisticated approaches to modeling hydrological processes are available (see Martin and McCutcheon, 1999; Singh, 1995 for comprehensive reviews), a shortage of appropriate hydrological data for the watershed precludes a more complex assessment of erosion–sediment relationships in the model.

The policy dimension of the model consists of crop-specific taxes and subsidies, crop-specific incentives on the costs of production, household-specific interventions that alter access to inputs and credit, and policies to alter price variability in all or specific crops. These values are connected to land use decision variables. The model allows us to vary the rate of any of these tax instruments and observe the effects on land use, farm income, erosion, sediment accumulation and damage, and public sector budgets.

The representative farms are modeled as making crop portfolio decisions under uncertainty. We assume a mean–variance utility function in which a farmer attempts to maximize expected utility (assumed to be a weighted-sum of mean returns and expected variance in returns). The decision-maker optimizes over a single cropping period and is myopic with respect to the future impacts of current decisions. This approach must be contrasted with an approach that assumes perfect foresight on the part of resource managers. In a perfect foresight case, decisions made in initial periods would be dynamically optimal, in the sense that choices would be optimal at all subsequent points along the planning horizon.

The household level model is specified as

$$\max_{\theta_i} \sum_{i=1}^{n} \beta_i \theta_i - \frac{\rho}{2} \sum_{i=1}^{n} \sum_{h=1}^{n} \sigma_{ih} \theta_i \theta_h \tag{1a}$$

$$\text{s.t.} \quad \sum_{i=1}^{n} \theta_i \leq 1, \quad \theta_i \geq 0 \quad \forall i \tag{1b}$$

where

$$\beta_i = (1 - t_i) p_i y_i - (1 - s_i) c_i \tag{1c}$$

Variables in Eqs. (1a)–(1c) are defined as follows: θ_i is the share of land planted with crop i, β_i the mean return for crop i, σ_{ih} the price variance for $i = h$ and the covariance for $i \neq h$, and ρ is the coefficient of risk aversion. The mean return for each crop is computed as the market price for the respective crop p_i adjusted for the tax (or subsidy) imposed on that crop t_i, multiplied by the crop specific yield y_i, after which input costs, c_i, net of any subsidies s_i, are deducted. For simplicity we assume a unit cost function for each crop and normalize planted area to be 1 ha. Cost parameters and cost functions are farm specific. Each representative household forms a two-crop portfolio.

Erosion on-farm k at time t, $E_{k,t}$, is a function of crop composition, slope, soil type and rainfall. In each period the flow of erosion affects two stock variables. First, erosion decreases the soil stock. The equation of motion for the farm-specific soil stock $S_{k,t}$ is

$$S_{k,t} = S_{k,t-1} - E_{k,t} \tag{2}$$

where the soil stock at time t equals the soil stock at time $t - 1$ minus the flow of erosion in period t. Erosion increases the stock of sediment Q_t that accumulates at the receptor site. Defining w_k as a farm-specific erosion–sediment transfer coefficient and δ_j as a zone-specific sediment-delivery delay parameter, we can write the accumulation of sediment at the receptor site according to

$$Q_t = Q_{t-1} + \sum_{\tau=0}^{t} \sum_{j=1}^{m} \delta_j \sum_{k=1}^{q} w_k E_{k,\tau} \tag{3}$$

where t equals the number of periods in the history of the simulation, m equals the number of zones, q equals the number of representative farms within each zone, and E is defined as above. Note that past erosion events contribute to sediment according to a delay specified by δ_j.

The model incorporates a positive feedback loop. During each planting season the farmer chooses an optimal crop portfolio. This crop portfolio, in combination with the physical factors discussed above, results in erosion that decreases the soil stock. We model the feedback by formulating crop-specific production functions that include the soil stock as an input.

sThe model provides measures of welfare at the level of the household, the zone, or the watershed, based on agricultural incomes inclusive of environmental damages affecting the productivity of agricultural land. These can be computed at a point in time, or expressed as the present discounted values of the stream of incomes, summed across households. The measures are subject to some potentially important limitations. They exclude off-farm incomes, utility considerations in the conservation or loss of environmental amenities, and the effects of damages or abatement expenditures in non-farm sectors such as hydro power generation. Moreover, although tax and subsidy interventions imply additional fiscal measures if long-run budget balance is to be maintained, we impose no such requirement on the fiscal authority, implicitly assuming that budget balance is maintained through accommodating transfers (e.g. from central government). Each of these features is the subject of ongoing refinements to the model. Further details of the model are provided in Appendix A.

2.3. Empirical implementation

The Manupali watershed is located in north central Mindanao, in the province of Bukidnon. The watershed catchment is approximately 60,000 ha, extending from Mt. Kitanglad in the northwest to the Pulangi river in the southeast. The watershed has an average elevation of 600 m a.s.l. Average rainfall is 2300 mm with rainfall peaks in June and October. Soils in the area range from slightly to strongly acidic clay and clay loams. Previous analyses (e.g. Bin, 1994) identify six major agroecological zones in the watershed, with an agricultural environment that can be roughly divided into three distinct groups. Two of these are upland agricultural areas and one is a lowland paddy rice zone concentrated in lower elevations on slopes less than 2°. The latter zone is not incorporated into this analysis. Instead, our empirical implementation of the model focuses on four representative households occupying the two representative upland agroeconomic zones in the Manupali watershed.

Fig. 1 is a flow chart that illustrates the process of model construction and the utilization of empirical data for calibration and parameterization of the model. As the chart indicates, the model makes use of two main sources of information. First, socioeconomic data, including panel data described in Coxhead et al. (2001) are used to define resources and resource constraints, and to inform household level models of behavioral response. Second, land-use data are used to calibrate and develop initial conditions in the model. These data are also used to develop weights and scaling parameters for representative households

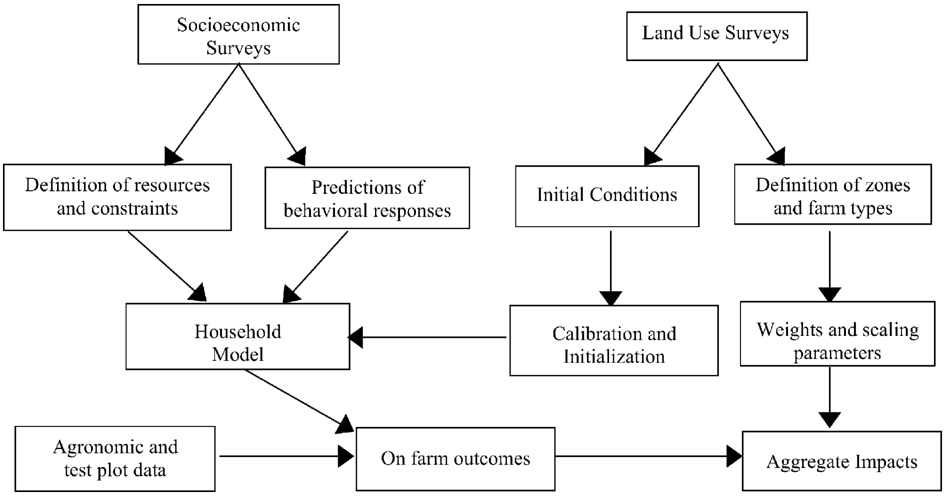

Fig. 1. Flow chart illustrating the process of model construction and data support.

Table 1
Cropping patterns and sample-proportions for representative farms in model

	Resource-constrained farms	Unconstrained farms
Zone 1 (forest-buffer)	White corn, coffee (60%, 40%)	White corn, vegetables (35%, 65%)
Zone 2 (mid-watershed)	White corn, coffee (40%, 60%)	White corn, yellow corn (60%, 40%)

Source: Computed by the authors based on data reported in Rola et al. (1999).

and zones. We also rely on several sources of agronomic and test plot data collected in the watershed (see Poudel et al. (2000) and references cited therein).

Table 1 briefly describes cropping patterns for each type of household in the two zones of interest. Data in Table 1 are based on detailed farm survey data reported in several sources including Coxhead (1995), Coxhead and Rola (1998) and Rola et al. (1999). Each representative household listed in Table 1 is defined in terms of a two-crop portfolio. The table lists primary crops for each household, as well as the land shares characteristic of these households within the watershed. This typology is a simplification, since in reality many households have the option of choosing from a much wider set of crops. Similarly, few households are strictly limited to a two-crop portfolio. Nevertheless, the typology in Table 1 reflects essential patterns of production in the upper portion of the Manupali watershed, represents approximately 90% of the cropped area in the upper part of the watershed, and captures a significant degree of the variation in land use and outcomes.

Models used to simulate farm level behavior were calibrated to replicate as closely as possible data reported in Table 1, using 1996 as a base year. The main policy parameters are crop-specific taxes t_i, crop-specific input subsidies, s_i, and a set of parameters that govern the relative variability of incomes associated with the crops in the model γ_i. In the case of tax and subsidy parameters, the policy variables take values between -1 and $+1$, corresponding to proportional taxes or subsidies on the respective crops. The model is calibrated so that outcomes generated with policy parameter values of 0 replicate sample data from the watershed. The status quo situation in the model reflects conditions in the watershed as of 1996, the reference year for base data in the model. The status quo situation is itself characterized by a constellation of direct and indirect policies affecting the agricultural sector. See Coxhead (1997).

Table 2 indicates the relative proportion of land in each zone represented by each farm type. The most widely grown crop in the upper Manupali watershed is white corn (*Zea mays* L.), which occupies approximately 48% of all cultivated area in the upper watershed. Although a market for white corn exists in the area, households typically grow the crop for home processing, storage, and consumption. Nearly all households in the upper watershed grow white corn. Following white corn in importance (in terms of occupied area) are coffee (*Coffea* spp.) (30%), yellow corn (*Z. mays* L.) (12%), and vegetables (10%). Vegetables occupy a relatively small share of total agricultural area, but vegetable production has grown in popularity in recent years and is economically important. We base our analysis for vegetables on detailed data observed for cabbage production (*Brassica oleracea* var. *capitata* L.). Cabbage is an important vegetable crop in the watershed in terms of value. In terms of production and market characteristics it is representative of a range of vegetable crops grown in the area, including potato and tomato. Due to highly erosive and chemical-intensive production practices, vegetable production has become a policy concern in the area. Table 3 contains average slopes for each zone and erosion rate estimates (by slope) for the major crops grown in the zones. These estimates are used as parameters for farm-level erosion predictions in the model. Erosion rates in the

Table 2
Area–share weights for representative households in model

	Share in zone based on area	Overall share based on area
Zone 1 (forest-buffer)	1.00	0.25
White corn, coffee	0.40	0.10
White corn, vegetables	0.60	0.15
Zone 2 (mid-watershed)	1.00	0.75
White corn, coffee	0.60	0.45
White corn, yellow corn	0.40	0.30

Source: Computed based on data in Coxhead and Rola (1998) and Rola et al. (1999).

Table 3
Average slopes and estimated erosion rates used in model

	Zone 1	Zone 2
Average slope	34.5	10.7
Average erosion rate (t/ha per year)		
Coffee	10.5	6.5
Corn	41.6	25.0
Vegetables	83.0	50.0

Source: Slopes calculated using data reported in Bin (1994) Table 5.2. Erosion rates adapted from David (1984) Table 5 using data reported in Cruz et al. (1988).

model are crop and zone specific so that crop production for the same farm type is more erosive when that farm type is located in a more erosion-prone zone of the watershed. For the purpose of modeling coffee area, we assume coffee planters in the model remain coffee planters, and adjust their effective coffee area in response to changes in incentives. We also assume households that have not planted coffee in the past do not initiate coffee production. This relieves us from having to explain tree planting and growth.

3. Results

We turn to results from policy simulations conducted with the model, as implemented using STELLA, a software package designed to model dynamic systems. We focus on assessing economy–environment trade-offs associated with four stylized policy interventions. These are (1) a 10% output price subsidy for white corn; (2) a 10% input cost subsidy for vegetable producers; (3) a 10% output price tax on vegetables; (4) a 10% reduction in price variance for all crops. In all cases, we conduct simulations under the assumption of a 10-year time horizon and assume the policy change is sustained for the full 10 years. For sake of comparison, we convert incomes and budgets to net present values (using a real discount rate of 5%) and express results relative to outcomes in the base run of the model.

Before highlighting results from the simulations, we draw attention to results from the base run of the model. These results are presented in Table 4. The initial columns of the table list the optimal crop shares for each crop and each representative farm. Incomes decline slightly over time in response to soil losses and declining yields. Erosion rates, which are reflective of crop shares on each farm, are stable in the base run of the model—except in household 4, where the erosion rate falls slightly over the 10 years due to a gradual shift of land from vegetables into corn. Results from the policy simulations are presented in Table 5.

3.1. A subsidy to corn producers

Given the importance of white corn within the watershed, we begin with an investigation of potential economic and environmental impacts of a 10% subsidy (sustained over the 10-year period) to white corn producers. This simulation is suggestive of a broad level of support for low-income corn farms. Within the Philippines, upland corn producers are recognized as one of the poorest segments of the rural population. As a result, many agricultural policies target the development and improvement of marginal corn lands, including the improvement of corn yields. Although white corn has a limited market, some trade occurs and could be affected by a targeted price subsidy, such as those previously administered by the Philippine National Food Authority. Furthermore, a number of policies—such as those that seek to improve corn yields—would have an effect somewhat analogous to a price subsidy (see Coxhead and Shively, 1998).

The first row of Table 5 indicates the impact of the 10% price subsidy. Not surprisingly, the subsidy is welfare improving for farmers. On average, the net present value of farm income in the watershed is expected to rise by about 8% over the base case. In terms of budgetary impact, the subsidy results in a NPV outlay of just over 3600 pesos (US$ 96) per household over the 10-year period. The subsidy accrues to households in disproportionate shares, however. These range from 16% (for corn–coffee farms in zone 2) to 32% (for corn–coffee farms in zone 1). The subsidy leads to a 16% increase in erosion over the base run of the model. The increase in erosion results from a contraction of coffee area and an expansion of corn area. However, vegetable farms register a slight reduction in vegetable area, and a concomitant increase in corn area. This has the effect of reducing erosion. The subsidy creates an incentive for farms that grow both white and yellow corn to shift a slight amount of land from yellow to white corn. This results

Table 4
Base run simulation results

Year	Land shares								Farm income				Erosion			
	HH 1		HH 2		HH 3		HH 4		HH 1 (P/ha)	HH 2 (P/ha)	HH 3 (P/ha)	HH 4 (P/ha)	HH 1 (t/ha)	HH2 (t/ha)	HH 3 (t/ha)	HH 4 (t/ha)
	White corn	Coffee	White corn	Coffee	White corn	Yellow corn	White corn	Cabbage								
1	0.70	0.30	0.36	0.64	0.61	0.39	0.44	0.56	5226	8249	6900	4198	26	17	33	52
2	0.70	0.30	0.36	0.64	0.61	0.39	0.45	0.55	5257	8233	6874	4204	26	17	33	51
3	0.69	0.31	0.36	0.64	0.61	0.39	0.47	0.53	5236	8216	6847	4213	26	17	33	53
4	0.69	0.31	0.36	0.64	0.61	0.39	0.48	0.52	5214	8199	6819	4225	26	17	33	51
5	0.69	0.31	0.36	0.64	0.61	0.39	0.50	0.50	5192	8182	6790	4243	26	17	33	50
6	0.69	0.31	0.36	0.64	0.61	0.39	0.52	0.48	5169	8165	6760	4266	26	17	33	49
7	0.69	0.31	0.36	0.64	0.61	0.39	0.54	0.46	5146	8147	6730	4295	26	17	33	49
8	0.69	0.31	0.36	0.64	0.61	0.39	0.56	0.44	5122	8129	6697	4332	26	17	33	48
9	0.69	0.31	0.36	0.64	0.61	0.39	0.59	0.41	5098	8110	6664	4378	26	17	33	47
10	0.69	0.31	0.36	0.64	0.61	0.39	0.61	0.39	5072	8091	6629	4435	26	17	33	46

Table 5
Summary of simulation results

	HH welfare (NPV/NPV_{BASE})	NPV budget (change from base)	Erosion (% change from base)
White corn subsidy (10%)	1.08	−7229	1.16
Vegetable cost subsidy (10%)	0.99	−6539	4.98
Vegetable tax (10%)	1.06	1666	−9.09
Variance reduction (10%, all crops)	1.01	NA	0.56

in an income gain for these farms, but no change in erosion.

It is important to point out that the main mechanism by which a tax (or subsidy) influences an agricultural producer is by changing the relative price the grower receives for a crop. But the tax (or subsidy) also influences the risk–return relationship associated with crops in the portfolio, and this effect is important if producers are risk averse. In the model, producers benefit less by a price rise than the full amount of the price subsidy because, in effect, they do not fully disengage from production of alternative crops due to a desire to balance risks by growing a portfolio of crops. In summary, the subsidy produces an increase in household welfare, but the increase is less in percentage terms than the incentive itself. The policy improves household welfare but increases erosion and places a burden on the public budget.

3.2. An input subsidy to vegetable producers

Vegetables are widely perceived by farmers and policy makers as a high value crop. In part this reflects significant protection of domestic producers from imports at the national level. Vegetable producers have also benefited in the past by a number of government policies that subsidized high cost inputs such as imported fertilizer and pesticides. These programs have tended to increase the number of vegetable farmers in the country, creating a lobby for support and protection of vegetable production. In the second simulation we investigate the impact of a subsidy directed at purchases of inputs for vegetable production.

The second row of Table 4 shows the impact of a sustained 10% input subsidy for vegetable producers. Although one might expect such a policy to be welfare improving, somewhat surprisingly the subsidy reduces the net present value of aggregate farm income by about 1% over the 10-year period. This paradoxical result occurs, in part, because the subsidy encourages vegetable production. In the initial years of the subsidy, vegetable farms shift their portfolios from corn to vegetables and receive higher net incomes than in the base run of the model. The long term effect of greater vegetable production is faster soil depletion and lower vegetable and corn yields in subsequent periods. The initial rise in vegetable production reduces the long-run income trajectory for farms that grow vegetables. Erosion is approximately 5% higher in this case than in the base case, and the NPV of public expenditures is approximately 1600 pesos (US$ 43) per household. It is important to point out that these results are driven by three important features of the model: (1) decision makers are assumed to be myopic and do not anticipate future reductions in yields and incomes; (2) yields are assumed to be responsive to changes in the soil stock; (3) NPVs depend on the chosen value for the discount rate. At higher discount rates, future reductions in yields and incomes count less and impatient producers could see a reduction in cost as beneficial overall, even though the long-run effect would be to reduce yields and income.

3.3. A tax on vegetable producers

If a subsidy to vegetable producers is detrimental to incomes and the environment in the long run, is it possible that a tax on vegetable production would be beneficial? In fact, the story that emerges from a 10% tax on vegetable production suggests so. In the case of the tax, the main effect is to discourage vegetable production. As a result, vegetable–corn farms deplete soil less rapidly, vegetable and corn yields are maintained at a higher level, and incomes fall by less than the amount of the tax. In effect, the tax has the effect of causing vegetable–corn producers to “internalize” the on-farm effect of soil erosion, much in the same way that a farmer with perfect foresight might. In this case, the policy raises the aggregate NPV of farm income by about 6% over the base, increases the NPV of public revenue (by approximately 400 pesos (US$ 11) per household) and reduces erosion by 9% compared with the base case.

3.4. Market stabilization

The impacts of efforts to provide stabilization in rural agricultural markets also can be studied with the model using crop-specific measures of price variability. As an example, efforts to strengthen market performance by improving physical infrastructure (e.g. roads and bridges) can reduce price variability for some crops. This, in turn, can influence production decisions because farmers are encouraged to plant less risky crops. The overall response to changes in price risk depends, in part, on the farmer's sensitivity to income risk.

Here we simulate the impact of a policy that lowers price and income variability for all crops in the watershed. This policy is easy to imagine. Investments to repair a bridge or improve a road can reduce the risk of transport failure, thereby creating cost savings throughout the marketing channel. As one might expect from a policy that reduces risks for all crops, the overall impact of the variance reduction on portfolio shares is small. It is not negligible, however. The policy encourages a slight shift in portfolios toward vegetables. For coffee–corn households the policy also encourages more coffee production. On net, the NPV of incomes rises approximately 1% from the base run of the model (which predicts about a 5% decline). Erosion increases slightly compared with the base case.

4. Model limitations

From a critical perspective, several limitations in our approach can be identified. First, while the model is quite rigorous in the way economic linkages are modeled, it nevertheless remains naïve with regard to hydrological processes. In part, this reflects data shortages. We use crop- and slope-specific erosion rates largely because these data, collected from run-off plots, are those that soil scientists typically collect. As a result, we find it difficult to model larger-scale processes such as soil deposition (that might increase productivity on some plots) or interactions between plots. As better data become available such phenomena may come within reach of those seeking to connect economic and environmental processes in models that easily facilitate desk top simulation in real time. For the time being, however, such modeling remains an elusive goal and the continued improvement of aggregated plot models seems warranted.

It is also important to point out that, while our approach places the farm household at the center of attention, the model remains somewhat simplistic in its view of household behavior. We have assumed just four representative households, a two-crop portfolio for each, and myopic optimizing behavior. Similarly, we have set aside for the purposes of this analysis such features of the landscape as the labor market, livestock production, and use of forest products and fallow. While modifying the model to account for some of these features is possible (see Shively and Zelek, 2002), the increase in insights afforded by modifications may be small. For example, adding additional crops to the model complicates the analysis and reporting of results, and provides only small improvements in predictive power, largely because most of the farm-level incentives associated with diversification strategies are captured by a small crop portfolio and the majority of land uses are represented by a relatively small number of crops.

5. Conclusion

We present a model that uses four representative households and a stylized two-crop portfolio to characterize the agricultural landscape of an upland watershed in a developing country. Simulations results show how input and output pricing policies can have deleterious effects on the environment, but also show that in some cases policies that appear detrimental to producers—such as a modest tax on production of highly erosive crops—can produce welfare gains by discouraging patterns of land use that are unsustainable in the long run. These are the results obtained when externalities or myopia (whether due to poverty, lack of information, or some other source) lead to socially suboptimal land use decisions by individual farm households.

Our analysis shows how a stylized model of a watershed economy can illuminate the potential impacts of policies. Such results can help policy makers to understand and identify the benefits and costs of policy alternatives, thereby improving the chances for sound watershed management (Heathcote, 1998). Results, such as those in Table 5, provide clear indications of the direction of change and potential magnitude of effects, and we have used these simulation results in academic and non-academic settings to improve dialogue and debate regarding management of the Manupali watershed. There, local government is coming to grips with the challenges of protecting and managing natural resources, subject to the extraordinary constraints under which developing-country resource management decisions are made and implemented (Coxhead and Buenavista, 2001). Analysis such as that presented here can help, by focusing attention on key issues and trade-offs.

Clearly, however, some important and relevant issues remain to be studied. Useful extensions might include the modeling of new crops or technologies, or the potential impacts of efforts to promote-specific technologies (e.g. vegetative strips, agroforestry systems, improved crop varieties). Empirical studies of technology adoption processes can provide guidance regarding possible patterns of adoption among representative farms, depending, for example, on land tenure security or resource constraints. With the help of spatial information from a GIS database, the economic and environmental impacts of efforts to promote or restrict certain types of activity—for example, through land use regulation by agroeconomic zone—can also be assessed in this type of model. Finally, the linking of agricultural and environmental policy initiatives to the broader economic and policy activities of communities and local governments is a very promising area for further research.

Acknowledgements

An earlier version of this paper was presented at the ICRAF methodology workshop on Environmental Services and Land Use Change in Southeast Asia. We thank David Midmore, Charles Zelek, two anonymous reviewers and workshop participants for helpful comments and suggestions. Financial support was provided by the SANREM CRSP, under USAID award RC710-006/5912994.

Appendix A. Details regarding the mathematical model

A.1. Analytical solution

The objective function in Eq. (1) may be written as the Lagrangian:

$$\max_{\theta_1,\theta_2,\lambda} L=\beta_1\theta_1+\beta_2\theta_2-\frac{\rho}{2}(\theta_1^2\sigma_1+2\theta_1\theta_2\sigma_{12}+\theta_2^2\sigma_2) -\lambda(\theta_1+\theta_2-1) \tag{A.1}$$

where subscripts 1 and 2 denote the two crops. Note that because the θ_i's are share variables and are expressed as the proportion of the farm area allocated to the respective crop, the sum of the shares is one. Differentiating the objective function with respect to θ_1, θ_2, and λ, the resulting first order conditions are

$$\frac{\partial L}{\partial\theta_1}=\beta_1-\frac{\rho}{2}(2\theta_1\sigma_{12}+2\theta_2\sigma_{12})-\lambda=0 \tag{A.2a}$$

$$\frac{\partial L}{\partial\theta_2}=\beta_2-\frac{\rho}{2}(2\theta_1\sigma_{12}+2\theta_2\sigma_{12})-\lambda=0 \tag{A.2b}$$

$$\frac{\partial L}{\partial\lambda}=-\theta_1-\theta_2+1=0 \tag{A.2c}$$

Solving this system of three equations provides three closed form solutions for θ_1, θ_2 and λ:

$$\theta_1^*=\frac{\beta_1-\beta_2+\rho\sigma_2-\rho\sigma_{12}}{\rho(\sigma_2-2\sigma_{12}+\sigma_1)} \tag{A.3a}$$

$$\theta_2^*=-\frac{\beta_1-\beta_2+\rho\sigma_{12}-\rho\sigma_1}{\rho(\sigma_2-2\sigma_{12}+\sigma_1)} \tag{A.3b}$$

$$\lambda^*=\frac{-\theta_1\sigma_2+\beta_1\sigma_{12}+\sigma_{12}\beta_2-\rho\sigma_{12}^2-\sigma_1\beta_2+\sigma_1\rho\sigma_{12}}{\sigma_2-2\sigma_{12}+\sigma_1} \tag{A.3c}$$

where λ is the shadow value of the land constraint for the household.

To incorporate policy parameters that might possibly affect income variance, the variance and covariance terms are modified as follows:

$$\sigma_i^* = \sigma_i(1+\gamma_i)^\gamma \tag{A.4a}$$

and

$$\sigma_{ih}^* = \sigma_{ih}\sqrt{(1+\gamma_i)(1+\gamma_h)} \tag{A.4b}$$

where γ_i is a variance-adjusting policy parameter for crop i. Examples of policies that could reduce income variability for specific crops include research into pest-resistant varieties or programs targeted at improving post-harvest handling for certain crops.

A.2. Aggregation

Using r to represent the discount rate and $\beta_{k,t}$ to represent net income at time t for household k and using ω and ν to represent area weights for representative households and zones, respectively, the net present value (NPV) formula for the household is

$$W_k = \sum_{t=0}^{T}\left(\frac{1}{1+r}\right)^t \beta_{k,t} \tag{A.5a}$$

For the zone it is

$$W_j = \sum_{k=1}^{q}\omega_k \sum_{t=0}^{T}\left(\frac{1}{1+r}\right)^t \beta_{k,t} = \sum_{k=1}^{q}\omega_k W_k \tag{A.5b}$$

And for the watershed it is

$$W = \sum_{j=1}^{m}\upsilon_j \sum_{k=1}^{q}\omega_k \sum_{t=0}^{T}\left(\frac{1}{1+r}\right)^t \beta_{k,t} = \sum_{j=1}^{m}\upsilon_j W_j \tag{A.5c}$$

A partial measure of the impact of policies on the government budget can be calculated based on taxes and subsidies applied to crops or inputs. The budget is partial in the sense that we can compute the costs of taxes and subsidies on crops or inputs, but cannot compute the costs of policies that might effectively stabilize markets (e.g. infrastructure improvements) or alter land tenure arrangements In terms of the entire watershed, this partial measure of the budget impact of a policy depends on the intervention (tax or subsidy rates), the behavioral outcomes at the farm level (e.g. crop choice), and the household or zone-specific weights applied to representative households. The NPV computation is

$$B = \sum_{t=0}^{T}\left(\frac{1}{1+r}\right)^t \sum_{j=1}^{m}\upsilon_j \sum_{k=1}^{q}\omega_k \times \sum_{i=1}^{n}\theta_{i,k,t}(t_{i,t}p_{i,t}y_{i,k,t} - s_{i,t}c_{i,t}) \tag{A.6}$$

The computation of the NPV explicitly recognizes that tax or subsidy rates may be altered over time. It is also possible for the government's discount rate to differ from that of individual households.

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