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The tradeoff analysis model: integrated bio-physical and economic modeling of agricultural production systems

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Abstract

There is an increasing call for tools that provide insight into the complex nature of agricultural systems and that deal with a broad range of sustainability issues related to policy intervention, technological innovations, and changes in environmental conditions (e.g., climate change). Sustainability indicators are useful, but only if their number is limited and the interactions between indicators are taken into consideration. In this context, we propose a methodology for an integrated analysis of tradeoffs between economic and environmental indicators. The analysis to quantify these relationships should be based on a multi-disciplinary approach and as such requires the usage of bio-physical as well as econometric-process simulation models. The communication between these very different models is based on explicit definitions of spatial and temporal scales and model integration software. The methodology is based on spatially explicit econometric simulation models linked to spatially referenced bio-physical simulation models to simulate land use and input use decisions. The methodology has been applied for the potato–pasture production system in the Ecuadorian Andes. Results of the analysis are presented in the form of tradeoff curves between different indicators, but also as maps, and risks diagrams. Besides an analysis of the current status, the approach allows for the analysis of alternative scenarios showing the effect of those scenarios on the position and slope of the tradeoff curve.

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1. Introduction

Agroecosystems are arguably the most important managed ecosystems in the world. An increasingly diverse array of leading public policy issues – including sustaining agricultural livelihoods, protecting water quality and other natural resources, and assessing global climate change mitigation strategies – create a demand for information about the economic and environmental properties of agricultural production systems. To make informed decisions, public stakeholders ranging from community leaders to national policy decision makers need to be able to assess how agricultural systems respond to changes in external stimuli such as changes in production technologies, policies, and shocks such as climate change.

Crissman et al. (1998a) proposed Tradeoff Analysis (TOA) as a process designed to integrate public policy decision makers and other stakeholders with a scientific team in order to provide quantitative information to support policy decision making about agricultural production systems. This process is illustrated in Fig. 1. Input from stakeholders (the general public, policy makers, and other interested groups) and scientists is used to identify the critical dimensions of social concern, i.e., criteria for assessment of the sustainability of the system, that we refer to as sustainability indicators. Hypotheses are formulated regarding the relationships between these sustainability indicators. These relationships may be in the form of competing objectives (tradeoffs) or complementary objectives (win–win) and are defined as tradeoff curves. Stakeholders and the scientific team also identify policy and technology scenarios of interest to the stakeholders that may shift the tradeoff curves. The next step in the process is for the scientific team to utilize suitable quantitative tools to simulate how these sustainability indicators behave under the scenarios identified by the stakeholders. These simulations are carried out at spatial and temporal scales appropriate for the processes involved, typically at the field scale for analysis of agricultural production systems. To provide information useful to policy decisions, these simulations must be carried out for a sample of bio-physical and economic units that is representative for the relevant populations, and the field-scale simulations results must be aggregated to a scale relevant for policy decisions. The final phase of the process is for the research team to communicate the results of the simulations to stakeholders in a form that is useful. Although the process is described as a linear process, there are a large number of feedback loops. After implementing research, certain indicators may be found less important than others that were not considered in the beginning. Preliminary results on tradeoffs may trigger new research (different indicators or other spatial or temporal scales).

This paper describes the Tradeoff Analysis Model, an integrated, GIS-based bio-physical and economic modeling system designed to work within the Tradeoff Analysis framework presented in Fig. 1. The Tradeoff Analysis Model is not a model per se but rather is a software package designed to be used by a team of scientists to integrate disciplinary data and models for tradeoff analysis. Users can apply the tool to

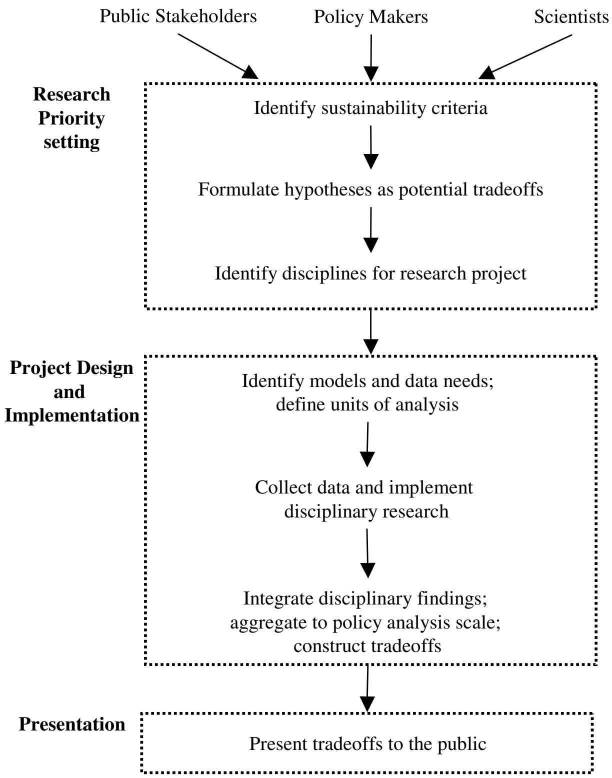

Fig. 1. Tradeoffs analysis research design and implementation process (Crissman et al., 1998a).

assess the sustainability of agricultural production systems under alternative technology and policy scenarios and to represent this information in various user-friendly graphical formats, including two-dimensional tradeoff curves, maps, and tables.

In Section 2 of this paper we provide the analytical foundations for Tradeoff Analysis through a formal derivation of the concepts of sustainability indicators, tradeoff curves, and scenarios, as well as the characterization of the decision making process of farmers. This discussion provides a formalization of the concept of sustainability as we propose it to be used. In Section 3, we describe the Tradeoff Analysis Model and in Section 4, we illustrate its use in a case study carried out in the Andean region of Ecuador.

2. Concepts and theory

2.1. Sustainability

Since the publication of the Brundtland report (WCED, 1987), the concept of sustainability has received increasing attention in agricultural research, yet researchers have struggled to operationalize the concept. Smyth and Dumanski (1993) sub-divided the general concept of sustainability into four main pillars representing productivity, stability of production, soil and water quality, and socio-economic feasibility. A slightly different approach for using the concept of sustainability has been to define various indicators (e.g., Pieri et al., 1995; Bockstaller et al., 1997). Several practical problems arise in implementing this strategy, including the large amount of data needed to quantify a large number of different sustainability indicators, and the challenge of understanding the complex interactions among such indicators. Some researchers have combined indicators into indices (e.g., Farrow and Winograd, 2001; Sands and Podmore, 2000; Van der Werf and Petit, 2002). This procedure raises the question of how indices measured in different units can be meaningfully aggregated. The choice of "weights" used for such aggregation is often arbitrary and lacks theoretical rigor. One well-known strategy for weighting different indices has been developed by economists for benefit-cost analysis, wherein systematic methods are used to ascertain monetary values to attribute to both market and non-market goods and services, including the services of natural capital. Yet even these systematic attempts to value and aggregate market and non-market goods have proved controversial and have not been widely accepted within and outside the economics profession (Portney, 1994; Belzer, 1999). The alternative approach taken in tradeoff analysis is to work with decision makers to identify a limited set of high-priority indicators, and then provide decision makers with quantitative estimates of the relationships among those indicators, leaving to the decision makers the task of subjectively assessing the implied tradeoffs or win–win options.

2.2. Tradeoffs

The concept of tradeoffs is fundamental to economics and derives from the idea that resources are scarce. Consequently, to obtain more of one scarce good, an individual or society collectively must give up some amount of another scarce good. Economists call this the principle of opportunity cost. Tradeoff analysis applies these principles to derive information about the sustainability of agricultural production systems, by quantifying the inter-relationships among sustainability indicators implied by the underlying bio-physical processes and the economic behavior of farmers.

Tradeoff curves are used to communicate information about tradeoffs to decision makers. Tradeoff curves are designed to embody the principle of opportunity cost in production systems. They are typically constructed by varying parameters in the production system that affect the economic incentives perceived by farmers in their land use and input use decisions. As farmers respond to changing economic incentives through changes in land use and input use, the sustainability properties of the production systems change. For example, in the potato/pasture production system discussed later in this paper, as potato prices increase relative to milk, farmers shift land use towards potato production, and also apply more inputs linked to potato management. The effect of these behavioral changes is increased pesticide use and the environmental and human health effects associated with pesticide use. Tradeoff curves defined with indicators such as value of production, pesticide leaching, and human health then can be used to show the tradeoffs between economic outcomes (greater farm income) and environmental and health outcomes (increased environmental contamination, increased health risks for rural populations). Thus, as a general principle, tradeoff analysis shows that for a given set of resources and technology, to obtain more of a desirable outcome of a system, less of another desirable outcome (or more of an undesirable outcome) is obtained. While there can be win–win outcomes in two dimensions, even such a win–win must come at the expense of some other desired attribute.

The analysis of tradeoffs proposed in this paper is based on an analysis of quantifiable sustainability indicators that are used to describe the behavior, performance, and impact of an agricultural production system across space and time. These indicators include, for example, economic performance (annual net returns, present discounted value of returns, distribution of returns, risk, etc.) and environmental performance (soil quality indicators like soil fertility, soil erosion, chemical leaching, etc.). As a practical matter, only a limited number of sustainability indicators can be analyzed for a given production system. It is therefore essential that in the tradeoff analysis process (Fig. 1), the key indicators are selected in a joint discussion between researchers and stakeholders. Tradeoff analysis recognizes that complex interactions between the indicators are a key aspect of production systems and represents these interactions as joint distributions of the selected indicators. The goal of the approach is to help decision makers understand those joint distributions and the implied interactions among the selected indicators.

Information about the joint distributions of indicators can be used in a joint learning process with decision makers. This process typically yields new questions to be answered by the research team and new insights to the decision makers. Tradeoff curves are two-dimensional graphs representing the tradeoff between two sustainability indicators. They show the relationship between two indicators, and thus the opportunity cost of changing one in terms of changes in the other. For example, in the analysis of the potato/pasture system discussed below, an increase in the value of production may come at a cost of greater pesticide leaching. In general terms, to construct a tradeoff curve, one model parameter (or a set of parameters) is changed while holding others constant. As this parameter is varied, the farmer changes land use and input use, and this generates changes in the various sustainability indicators for the system (for a formal derivation of tradeoff curves, see Antle et al., 1998b; Antle and Stoorvogel, 2001).

Many decision makers would like to have information about prospective or ex ante effects of policy or technology changes, or the effects of changes in bio-physical conditions caused by resource degradation or climate change. These types of exogenous changes in the drivers of the production system will result in a shift of the joint distribution of indicators, and thus will result in a shift in a tradeoff curve. We refer to this type of change in the system's exogenous drivers as a policy, technology, or resource change scenarios.

Fig. 2 presents a number of examples of hypothetical tradeoff curves between different outcomes and indicators of a production system. In Fig. 2(a) the tradeoff curve shows a positive correlation between agricultural production on the horizontal axis and soil erosion on the vertical axis. The relation indicates that if we increase agricultural production through, for example, higher prices for agricultural products, this change coincides with increasing soil erosion. Fig. 2(b) shows the tradeoff curve between current and future agricultural productivity. A 1:1 line indicates that current productivity is sustained in the future, or, in other words, there is no negative impact of current agricultural activities on the future productivity. However, Fig. 2(a) shows that a high agricultural productivity coincides with high erosion rates. As a result, future productivity decreases and we observe in Fig. 2(b) a relationship below the 1:1 line. When presenting current versus future productivity, the slope of the tradeoff curve can be seen an indication of the sustainability of the system (Antle and Stoorvogel, 2001). We should note, however, that this refers mainly to the first two pillars of sustainability as defined by Smyth and Dumanski (1993). Even if production is sustained, a system may have negative impacts on environmental quality, and tradeoff curves can be constructed to show relationships between various environmental indicators such as soil erosion and pesticide leaching as shown in Fig. 2(c). Erosion will result in a removal of topsoil material rich in organic matter and consequently reduces the soils' binding capacity. As a result increasing erosion rates coincide with increasing rates of pesticide leaching.

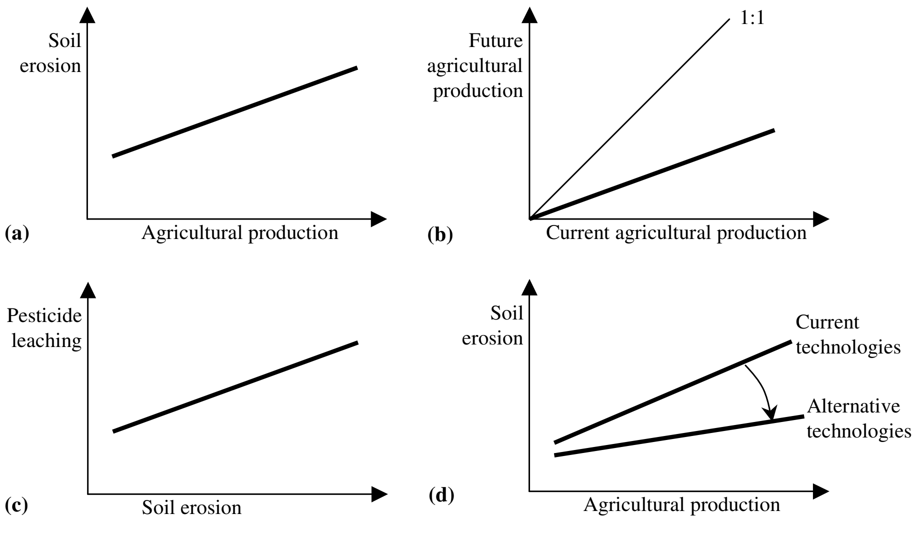

Fig. 2. Examples of possible tradeoff curves. (a) Increased soil erosion when intensifying agricultural systems. (b) The negative effects on future productivity as a result of soil erosion when intensifying current agricultural production. (c) Increased pesticide leaching as a result of increased erosion rates. (d) The impact of alternative (conservation) technologies on the tradeoff curve.

Policy or technology scenarios are analyzed by changing corresponding model parameters and observing the resulting shift of a tradeoff curve. An example of a technology scenario is shown in Fig. 2(d). In this example, the introduction of erosion control measures results in a shift of the tradeoff curve in a favorable direction in the sense that increases in output can be obtained with smaller increases in erosion.

2.3. Spatial and temporal scales and aggregation

The goal of tradeoff analysis is to support decision making related to public policy issues associated with agricultural production systems. Thus, the focus of tradeoff analysis is to provide information at a spatial scale relevant to such policy questions – typically a unit of analysis such as a watershed, a political unit, a region, or even at the national level. Yet, the environmental impacts of production systems are generally site-specific. A critical question, therefore, is how to bridge the gap from the site-specific impacts of agricultural production systems to the scale relevant for policy decisions. Hansen and Jones (2000) summarize a range of different procedures to minimize aggregation bias. Within the Tradeoff Analysis Model we sample in geographic and probability space to characterize the population of bio-physical and economic decision making units in a region. In an early stage, fields are sampled in a geographic space with or without certain spatial criteria. Subsequently, simulations for each field are carried out several times while sampling from the probability space for prices of inputs and outputs. The results of the simulations are aggregated to a regional scale relevant for policy analysis using tradeoff curves and other means of communicating results (Fig. 1). Depending on the objectives, aggregation can be a simple summing up of the individual simulation results to obtain average tradeoff curves or other procedures that present the results at the regional level in terms of risk or spatial coverages.

The Tradeoff Analysis Model makes use of a suite of bio-physical and econometric models to represent various bio-physical processes and farmer decision making. To link these models, compatible spatial and temporal scales must be used. For example, a pesticide-leaching model with a daily time-step cannot be linked to an economic model with a seasonal time step. One solution to linking models with different units of analysis is to utilize procedures for aggregation or disaggregation (Stoorvogel and Antle, 2001; Hansen and Jones, 2000).

2.4. Simulating land use and management decisions

A central component of any model of an agricultural production system is the characterization of how farmers make land use and management decisions. This section outlines the theoretical foundations of the economic modeling approach used in the Tradeoff Analysis Model and how it is transformed into a simulation model. This approach is based on the linkage of biophysical and econometric production models within a stochastic simulation framework. The resulting simulation model is referred to as an econometric-process model (Antle and Capalbo, 2001a).

To illustrate the spatial aspects of the analysis, we present here a simple static representation of a production system. We consider a region composed of a population of fields. The environmental characteristics of those fields are described by a vector $\mathbf{e}_{it}$ at field i in period t. Each production activity at field i for crop j in period t is described by a production function technology $\mathbf{q}_{ijt} = f(\mathbf{v}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})$, where $\mathbf{v}$ is a vector of variable inputs and $\mathbf{z}$ is a vector of allocatable quasi-fixed factors of production. The production function for each production activity is assumed to be non-joint in inputs, following Just et al. (1983). For simplicity, we assume that as a first-order approximation, farmers make decisions to maximize expected profit (this objective can be modified in obvious ways to allow for risk aversion and other objectives). Thus, corresponding to the production function is an expected profit function

$$\pi_{ijt} = \pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it}), \quad (1)$$

where p_{ijt} is expected output price and $\mathbf{w}$ is a vector of input prices.

We define $\delta_{ijt} = 1$ if the jth crop is grown on field i at time t and equal to zero otherwise. If the field is not in crop production then it is in a conserving use or other use that earns a return π_{ict}. Letting $\delta_{ict} = 1 - \sum_j \delta_{ijt}$, the land use decision is defined as solving

$$\max_{(\delta_{iqt},\ldots,\delta_{\mathrm{int}})} \sum_{j=1}^{n} \delta_{ijt}\pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it}) + \delta_{ict}\pi_{ict}. \quad (2)$$

The solution to this problem takes the form of a discrete step function

$$\delta^*_{ijt} = \delta(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{ict}), \quad (3)$$

where $\mathbf{p}_{it}$ is a vector of the expected output prices. Eq. (3) states that the farmer's discrete land use decision at the field scale is a function of crop prices, input prices, fixed factors of production, and the bio-physical conditions at the site.

Using the derivative properties of the profit function (Varian, 1992), the production on the ith field is given by the site-specific supply function

$$q^*_{ijt} = \delta^*_{ijt}\frac{\partial\pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})}{\partial p_{ijt}} = q_{ijt}(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{ict}). \quad (4)$$

Likewise, site-specific variable input demands are given by

$$v^*_{ijt} = -\delta^*_{ijt}\frac{\partial\pi_j(p_{ijt}, \mathbf{w}_{ijt}, \mathbf{z}_{ijt}, \mathbf{e}_{it})}{\partial w_{ijt}} = v_{ijt}(\mathbf{p}_{it}, \mathbf{w}_{it}, \mathbf{z}_{it}, \mathbf{e}_{it}, \pi_{ict}). \quad (5)$$

Eqs. (4) and (5) show that the site-specific variable input decisions and expected production on a field are functions of output prices, input prices, fixed factors, and bio-physical conditions. These functions take on a value of zero if a crop is not produced and take on the positive value indicated by profit maximization (or other suitable objective) when production does occur at that site. Other decision criteria such as expected utility maximization for risk analysis may be used (Antle and Capalbo, 2001b).

The solution to (2) applies to a given field, and is based on the assumption that each field can be managed separately. More generally, constraints on allocatable fixed inputs, risk, or non-separability of consumption and production decisions may lead to joint management of all fields. In many cases, economic production models do not include timing of specific management operations. However, to be able to evaluate the environmental impact of production systems, timing of management operations is an important characteristic determining to a large extent whether or not for example nutrient losses will occur (see, e.g., Van Alphen and Stoorvogel, 2000). Depending on the production system under consideration, the selected indicators, and the subsequent scenario analysis it may be necessary to develop dynamic production models to account for crop rotations or the endogenous timing of production decisions (see, e.g., Antle et al., 1994).

Antle and Capalbo (2001a) show how this theoretical decision-making framework can be transformed into a stochastic simulation model, by specifying systems of supply functions and factor demand functions (empirical analogs of Eqs. (4) and (5)) that can be estimated econometrically and then used to simulate the discrete land use decision represented by Eq. (3) and the input use decision and supply decisions (4) and (5). Antle and Capalbo argue that econometric-process models are well suited for use in integrated assessment of agricultural production systems: they can link land use and management decision making with bio-physical crop growth and environmental processes on a site-specific basis; they can realistically represent the spatial variability in economic behavior; and they can simulate discontinuities and non-linearities implied by the logic of the decision making process that are outside the range of observed behavior.

An important feature of the econometric-process modeling approach is the explicit linkage of bio-physical crop and livestock models with econometric production models. This linkage is designed to address a problem that has long plagued empirical production economics research, namely how to incorporate effects of soils and climate on productivity into economic production models. Production economists have long specified production functions in the general form $q = f(\mathbf{v}, \mathbf{z}, \mathbf{e})$, where $\mathbf{v}$ is a vector of variable inputs, $\mathbf{z}$ is a vector of fixed inputs, and $\mathbf{e}$ is a vector of bio-physical factors. In practice the bio-physical factors $\mathbf{e}$ are represented in econometric production models by using ad hoc indicators of soil quality and climate such as dummy variables for soil types and average rainfall during the growing season. The Tradeoff Analysis Model provides the capability to take an alternative approach to econometric modeling that exploits the scientific knowledge embodied in bio-physical process models. Theoretically, soil and climate conditions define the potential productivity of a location that, combined with a plant type, management practices, and weather conditions, leads to a realized output. Crop growth simulation models can be represented in stylized form as $q = g(\mathbf{v}, \mathbf{e})$. Defining average input use $\bar{\mathbf{v}}$, we can use the crop growth simulation to calculate an expected or inherent productivity q^* for a specific location on the basis of soil and weather data $q^* = g(\bar{\mathbf{v}}, \mathbf{e})$. We can now replace the vector $\mathbf{e}$ in the production function with the newly calculated inherent productivity: $q = h(\mathbf{v}, \mathbf{z}, q^*)$. Theoretically we can incorporate the crop growth simulation model resulting in our original form of the production function:

$q = h(\mathbf{v}, \mathbf{z}, q^*) = h(\mathbf{v}, \mathbf{z}, g(\bar{\mathbf{v}}, \mathbf{e})) = f(\mathbf{v}, \mathbf{z}, \mathbf{e})$. However, for pragmatic reasons the models are kept separate (Stoorvogel and Antle, 2001). Thus, the bio-physical models are used as a means to systematically transform site-specific bio-physical data into an estimate of the spatial or temporal variation in expected or inherent productivity. This is interpreted as a proxy for the site-specific information the farmer uses in making management decisions.

3. The tradeoff analysis model

In this paper we present an integrated modeling approach for the estimation of tradeoff curves. The Tradeoff Analysis Model puts into practice the integrated bio-physical and economic analysis needed to quantify tradeoffs. The usage of the Tradeoff Analysis Model should, however, be preceded by the research priority setting as identified in Fig. 1.

Fig. 3 provides a general overview of the modeling approach that can roughly be divided into four components dealing with data collection, model calibration and estimation, simulation of tradeoffs and scenarios, and the presentation of the results. Each of those four components will be discussed in the following sections. For a detailed description of the Tradeoff Analysis Model software, see Stoorvogel et al. (2001).

3.1. Data collection

Tradeoffs can only be established if the proper data have been collected that describe variations in agro-ecological conditions throughout the region and provide insight in the processes relevant for crop growth, environmental impacts, and decision-making. Communication among the research team is especially important during the planning for data collection. Comparable results from different disciplinary models are feasible only with linked disciplinary data. The data include environmental data (site-specific soil and climate data), farm survey data (site-specific production, input and price data), and experimental data for the calibration of the bio-physical models. The optimum methodology for data collection is dictated by the objectives of the analysis, but also by the variability in the study area. The temporal and spatial scales as defined in the project design prescribe the level of detail for the data collection effort.

3.2. Model estimation

The strength of the Tradeoff Analysis Model lies in the linkages between different disciplinary models. The models can be sub-divided in three main groups: (i) production models to estimate the inherent productivity of farmers' fields, (ii) environmental process models to estimate the environmental impact of farmers activities, and (iii) an econometric process simulation model describing the decision making process at farmers' fields in terms of land use and input use. These models can only function

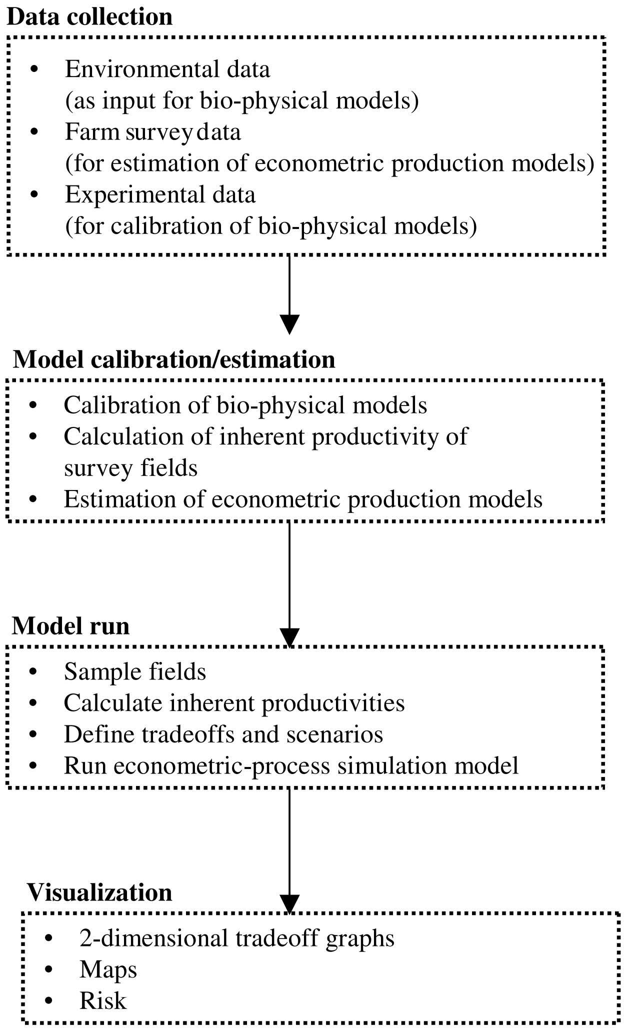

Fig. 3. General framework of the Tradeoff Analysis Model.

properly if they are calibrated to and estimated for the local conditions in the study area. Production models and environmental process models have to be calibrated. To estimate the econometric process simulation model we use the inherent productivity as an important driving factor behind the land use and input use decisions of farmers. It is therefore necessary to run the production models for the farmers' fields to estimate the inherent productivity. Subsequently, we can estimate the economic simulation model (a system of supply functions and factor demand functions for each activity). In addition, we estimate the distribution of input and output prices and the distribution of field size.

3.3. Simulation

Before analyzing a specific relation between the indicators, we have to specify how the tradeoff curve is to be constructed. The tradeoff definition includes a choice of variable, the number of steps for change of this variable, and the size of change between steps. We refer to these steps as "tradeoff points". When processed by the model, the tradeoff points define the shape and location of an individual curve for a given technology. Secondly, we can define different scenarios by changing model parameters. These changes in model parameters represent alternative technologies and/or policy interventions. These define different tradeoff curves. In the definition of the econometric simulation model, parameters can be added specifically to reflect certain changes of interest to the analyst. Examples can be found in the application in the following section.

Once the simulation parameters are set, the tradeoff model will sample a set of the fields from the total population of fields. Sampling takes place by randomly drawing a set of coordinates and verifying the coordinates against a set of user-defined spatial conditions (e.g., soil type, altitude). If the location is accepted, the field size is drawn from a given distribution and the inherent productivity of that particular field is assessed using the crop growth simulation model. Although it is possible to run the simulation for the original survey fields, the option to draw fields randomly from the area allows for extrapolation and stratification of the area.

Next, the actual simulation of land use and input use is initiated. A simulation run involves a large number of individual simulations. Decisions for each field are simulated several times (repetitions) under different conditions (tradeoff points). Each individual simulation run starts with drawing input and output prices from the distributions after which land use and input use decisions are simulated.

The output of the econometric simulation model includes land use and land management for each of the fields, under different conditions (the tradeoff points) and for several repetitions land use and input use. This output can subsequently be input for an environmental process model that estimates the impact of the specific decisions on that location in terms of, e.g., erosion.

The results of the different simulation runs provide insight in the varying conditions defined by the tradeoff points, the different price levels for inputs and outputs and the varying conditions in natural resources. Nevertheless, it is necessary for the interpretation to aggregate the results to have, for example, average values per tradeoff point. How results are aggregated depends on the interest of the user and their preferences for presenting the results.

3.4. Visualization

The model provides a variety of results presentation tools. Scatter plots can be created to display results as a joint distribution between two indicators. If the data are aggregated over, for example, the tradeoff points, the general trend of the tradeoff curve becomes clear (if necessary a line or curve can be fitted through the different points). Because the analysis is done on a geographic basis, i.e., the location of the different fields is known, this information can be used to plot the results on a map. The results for the individual fields can also be interpolated using, for example, inverse distance or ordinary Kriging, to provide a map with the spatial distribution of a certain indicator.

4. Tradeoff analysis for the potato–pasture zone in northern Ecuador

4.1. Study area

Carchi Province in northern Ecuador is typical of the northern humid páramo Andes. The agricultural system on the steep Andean hillsides is dominated by the production of potatoes and milk. The research focused on two watersheds corresponding to the San Gabriel and Chitan rivers encompassing a total area of 95 km^2 ranging in altitude between 2700 and 3800 m above sea level. Being located close to the equator there is virtually no change in average monthly temperature ranging from 9 to 12 °C. Average rainfall varies between 950 and 1300 mm/yr with significant year-to-year variation. Volcanic ash soils with their typical thick, black A-horizon, high organic matter content, and high infiltration capacity have developed in relatively young volcanic ash deposits. Crissman et al. (1998b) give a full description of the Carchi study site.

4.2. Research priority setting

Following the tradeoff analysis process described in Fig. 1, stakeholder meetings were held during early stages of the project to identify key sustainability indicators and their tradeoffs, and relevant policy and technology scenarios. Stakeholders identified the high level of pesticide use as an issue related to the economic survival of farmers, as well as for potential environmental and human health impacts. When we made our first visit to meet with stakeholders, several experts identified water erosion and the environmental impacts of pesticides as critical problems in the study area. However, after visiting the region we found little evidence of water erosion, and subsequent analysis of soil and climate conditions led us to understand that tillage erosion was the main process that threatens future productivity. Similarly, our research showed that human health effects related to pesticide use were much more significant than the risk of environmental contamination (Crissman et al., 1998a,b). The focus on the environmental impacts was the result of a policy debate in the 1980s that was largely driven by environmental groups claiming that pesticides were having significant environmental impacts. The above illustrates that the choice among key sustainability indicators is and will remain a delicate judgment on the part of the research team in collaboration with stakeholders.

To deal with the environmental and human health effects of pesticides and the process of tillage erosion, the research team decided to collect data that would allow processes to be simulated at the field scale, with daily time steps for pesticide application decisions.

4.3. Data collection

Data collection focused on three types of data: environmental data, farm survey data, and experimental data.

Environmental data describe the spatial variation in soils and climate and is organized in a GIS format. It is used as input to the biophysical models and, possibly, to stratify the study area. In the Carchi case study we made use of an existing soil survey for northern Ecuador (MAG and ORSTOM, 1980). However, the soil survey did not provide quantitative data on soil properties required to run the biophysical simulation models. In addition, the soil survey did not have the appropriate scale to be able to run simulation models at the field level. Specific data collection efforts were carried out to provide the quantitative data and to disaggregate the soil information using field observations in combination with a detailed digital elevation model.

Weather data from three meteorological stations in and around the study area were linked to a digital elevation model. A linear relation between altitude and weather conditions is assumed to describe the spatial variation in weather conditions.

A sample of 40 farmers with 187 fields was drawn from household records available to the research team. A two-year dynamic survey was conducted for those fields, with approximately monthly visits to each farmer to obtain data about management practices on each field they managed.

Crop growth simulation models and environmental impact models are used to describe the inherent productivity of farmers' fields and the environmental impact of farm management. These models need to be calibrated to local conditions using experimental data.

To simulate potato growth, we used the SUBSTOR-potato model (Ritchie et al., 1995) that was released with the Decision Support System for Agrotechnology Transfer (DSSAT v.3) (Jones et al., 1998). Using experimental data from the study area, the SUBSTOR model was calibrated to the local conditions in the Ecuadorian Andes (Bowen et al., 1999).

Pesticide leaching was simulated using the PEARL model (Tiktak et al., 2000). Wagenet et al. (1998) indicated the methodological problems that may arise while assessing the pesticide environmental impact in developing countries. They argue that a proper calibration of the mechanistic simulation models is almost never possible and that monitoring pesticide concentrations is often the most straightforward way to assess pesticide emissions to the environment. However, within the context of the tradeoff analysis model, we are not only interested in current emissions of pesticides, but also focus on possible emissions under alternative policy and technology scenarios. Therefore, the team set up experiments to quantify degradation, sorption, and lateral water flow, as well as a monitoring program of pesticide concentrations in the vadose zone, ground water and streams throughout the study area (Stoorvogel et al., 2003). Among the wide variety of fungicides and insecticides used by farmers in this region, carbofuran was identified as among those posing the highest environmental and human health risks using a screening procedure described by Van Alphen and Stoorvogel (2002). Carbofuran is a widely used insecticide applied to control the Andean Weevil (*Premnotrypes vorax*) and classified as highly hazardous (class Ib) by the World Health Organization (*www.who.int/pcs/docs/Classification of Pesticides 2000-01.pdf*).

Tillage erosion receives increasing attention from researchers developing methods to quantify mass transport of soil as a result of tillage (e.g., Turkelboom et al., 1999; Dercon, 2001). To quantify the current extent and rate of tillage erosion in the study area, 45 fields throughout the study area were surveyed by intensive augering and farmers were interviewed to determine land use history (Veen, 1999). The study yielded relations between mass transport and the explanatory variables slope, tillage, and soil type.

4.4. Model specification

First, the inherent potato productivity for the survey fields was determined using the GIS database and the SUBSTOR-potato model. The inherent milk productivity is based on a statistical relationship between altitude and production. Afterwards, the pesticide demand functions for the Carchi potato/pasture case are estimated using a system of equations representing both the quantity applied and the time intervals between applications following Antle et al. (1994, 1998a). In the farm survey 27 different insecticides and 41 different fungicides were used by farmers. These pesticides are composed of a wide array of organic and inorganic chemicals with different potencies. To be able to compare the applications of the different pesticides they were quality-adjusted in standardized units (Antle et al., 1998a). The demand equations represent quality-adjusted quantities of fungicides and insecticides, and carbofuran (not quality adjusted). For each type of pesticide, a two-equation reduced-form system is estimated representing quantity and timing of pesticide applications. These log-linear functions depend on input and output prices, field size, fertilizer, application time, and lagged quantity and timing variables to incorporate the dynamics of the sequential applications. The value of potato production is estimated using a revenue function specified in terms of quantities of pesticides applied during the season, previous crop, fertilizer, and field size. For milk production, the supply function estimated with the cost function is also used to generate a value of milk produced. To simulate the realized value of output, the estimated models are used to predict the mean value of output and estimated error variances for the models are used to construct random components of the output value.

4.5. Simulation

A total of 100 locations were sampled from the area for the simulation runs. Sampling was done randomly for the whole study area (excluding non-agricultural areas). For each of the locations, a field size was drawn from a statistical distribution and the inherent potato productivity was simulated for the hypothetical field using the SUBSTOR-potato model (Fig. 4). The dynamics in agricultural production in the potato–pasture system are dominated by the relative advantages of

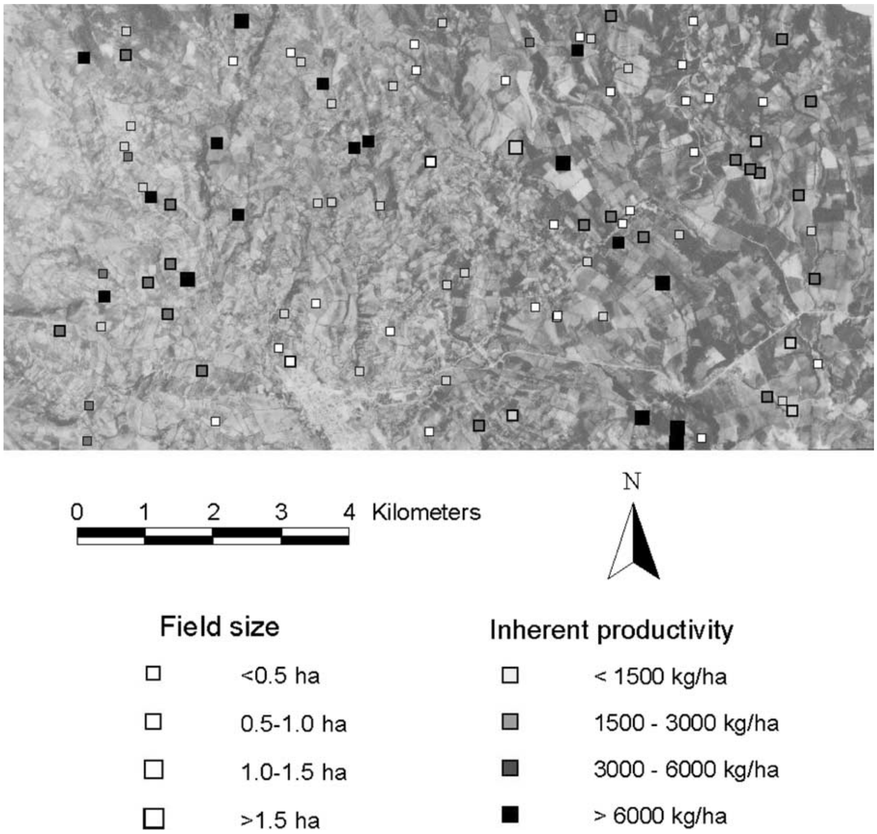

Fig. 4. The location, field size, and the inherent potato production of the sampled fields in the San Gabriel region of Carchi Province, Ecuador.

potato and milk production. The tradeoffs were constructed by varying mean potato prices to change the incentives of farmers to produce potatoes or pasture for dairy cows. Five tradeoff points were defined: two with 50% and 25% decreases in mean potato prices, one with the observed potato prices, and two with a 25% and 50% increase in mean potato prices. In the scenarios the econometric-process model was used to simulate land allocation and land management decisions for five crop cycles. The simulations yielded data on inputs and outputs and the timing of pesticide application decision.

Figs. 5(a) and (b) show examples of tradeoff curves illustrating the relation between net returns and carbofuran leaching as result of changing potato prices, i.e., the previously defined tradeoff points. Fig. 5(a) shows the actual variation in the tradeoff curve for a single tradeoff point (current prices). Although the variation is extremely relevant, it also makes the interpretation of the results rather difficult. To analyze the tradeoff curves, we therefore aggregated our simulation results over the five crop cycles, resulting in five observations per tradeoff point. Together, the

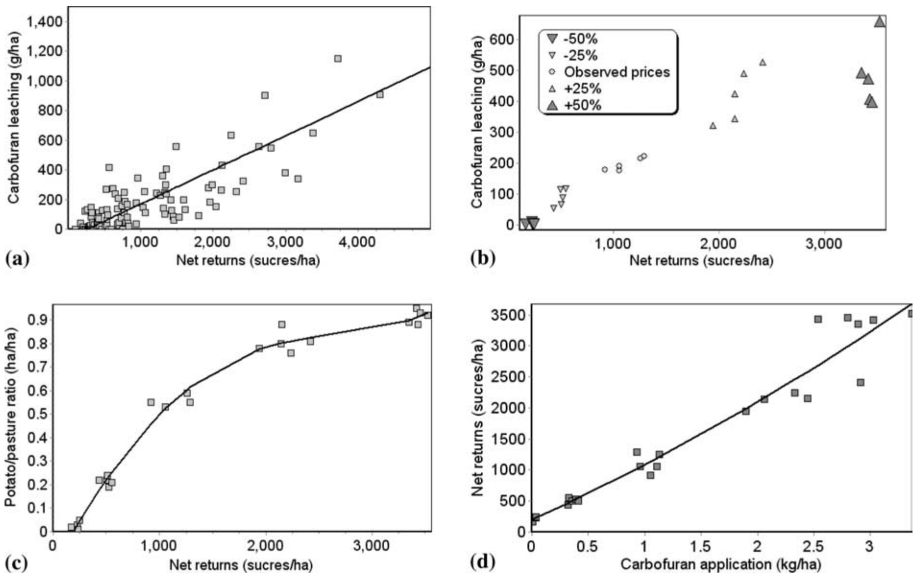

Fig. 5. The relation between net returns and carbofuran leaching under different potato price regimes (1800 Sucre ≈ 1 US$). (a) The variation in net returns and carbofuran leaching as a consequence of spatial variability under currnet price conditions. (b) The simulation results of the base scenario per tradeoff point. (c) The relative importance of potato in the crop rotaion as a function of net returns. (d) The effect of carbofuran application on net returns.

five tradeoff points constitute the tradeoff curve. In Fig. 5(b), the positive, generalized relationship between net returns, and carbofuran leaching is depicted. Why do we observe this positive relationship? The farm survey shows that with increasing potato prices farmers increase the inputs in the crop to protect their valuable potatoes. However, perhaps more important is the increasing importance of potato in the crop rotation. Fig. 5(c) shows the relation between net returns and the relative importance of the potato crop. It shows that with the low potato prices (50% under the observed prices) almost no potatoes are grown and with the high potato prices (50% above the observed prices), the potato crop constitutes 90% of all crop cycles despite the productivity loss with almost continuous cropping. Of course, one can select any set of indicators to be presented with the modeling system. Fig. 5(d) shows, for example, the relation between carbofuran application and net returns. Again the positive relation is a result of the increasing importance of the potato crop. Although aggregated tradeoff curves are very appealing, we have to realize that there is a large variability in the survey fields and each of the survey fields will yield its one specific set of outcomes. The variation in outcomes may be even more interesting than the aggregated results. At least a part of the variation is induced by differences in the environmental characteristics of the sampled fields. This can be checked by mapping the model results.

Fig. 6 shows the spatial variation in carbofuran leaching for each of the tradeoff points. The results for the different fields have been interpolated using ordinary

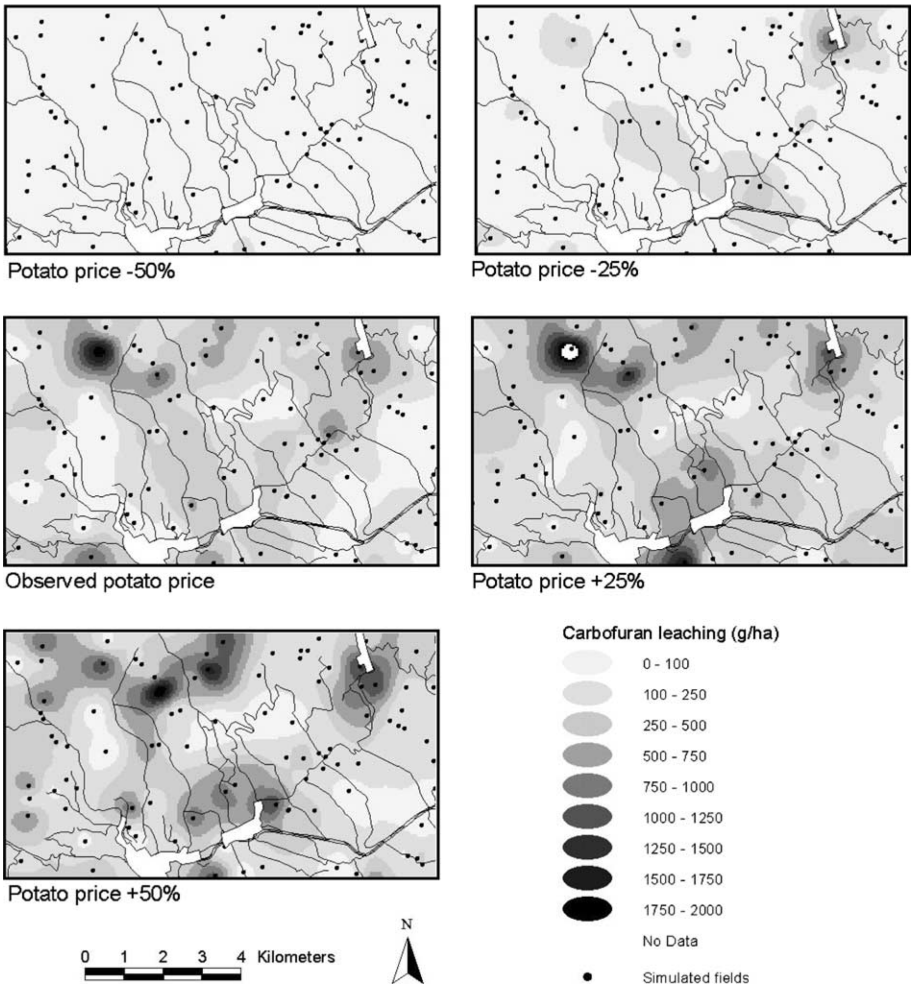

Fig. 6. The spatial variation in carbofuran leaching under different potato price regimes in the Carchi study area.

Kriging. The semi-variogram showed a strong spatial dependency in carbofuran leaching with a range of approximately 1 km. Fig. 6 clearly illustrates that the trade-offs as they are depicted in Fig. 5 should be interpreted with care. Large parts of the study area have a low risk for pesticide leaching even if potato production is being favored. Other areas, however, exhibit high risks for pesticide leaching even with low potato prices.

It is often useful to provide information to stakeholders (the general public as well as public policy makers) in terms that express the risk of environmental contamination or human health risk. These risk statements are often defined using thresholds for a significant risk. The Tradeoff Analysis Model is designed to provide the kind of

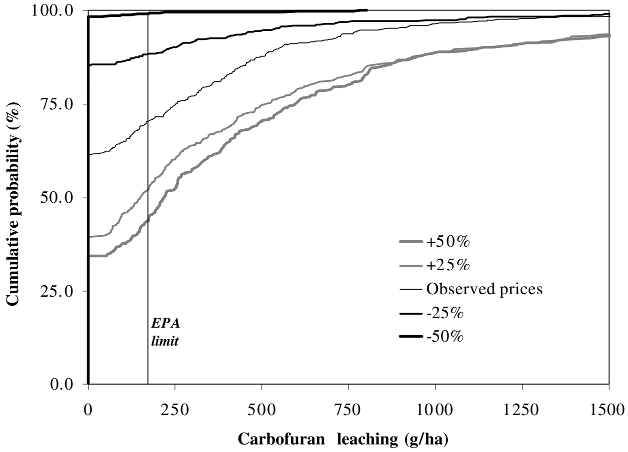

Fig. 7. Cumulative probability that threshold values for carbofuran leaching are met.

information needed to quantify such risks. To illustrate, Fig. 7 shows the cumulative probability that a threshold for carbofuran leaching is not exceeded under different potato price regimes. These probabilities are based on the simulations of 40 different fields for five different crop cycles. The cumulative probabilities indicate the percentage of the 200 cases in which carbofuran leaching does not exceed a threshold value. As very few governmental organizations have actually set pesticide-specific limits for groundwater contamination, we use the threshold defined by the United States Environmental Protection Agency (EPA) (maximum contaminant level) for carbofuran in drinking water to illustrate the usage of the tradeoff analysis. The EPA threshold for carbofuran is set at 40 ppb. [1] Given average drainage in the study area, this corresponds with approximately 160 g carbofuran/ha. Fig. 7 shows that at observed prices, about 30% of fields are likely to exceed the threshold contamination level in water leached below the root zone. With a 50% decrease in potato prices, 99% of all fields will stay under the EPA threshold, whereas if potato prices increase 50% from base values, about 60% are likely to exceed the threshold. This finding illustrates the power of the integrated modeling framework to quantify the interactions between biophysical and economic processes.

4.6. Scenarios

In this section we report the results of simulating two scenarios to illustrate the use of the Tradeoff Analysis Model. A first scenario deals with the introduction of an integrated pest management (IPM) technology for Andean weevil management. In addition, we assess the impact of changes in soils as a result of tillage erosion and the impacts these changes have for carbofuran leaching below the root zone.

[1] http://www.epa.gov/safewater/contaminants/dw_contamfs/carbofur.html

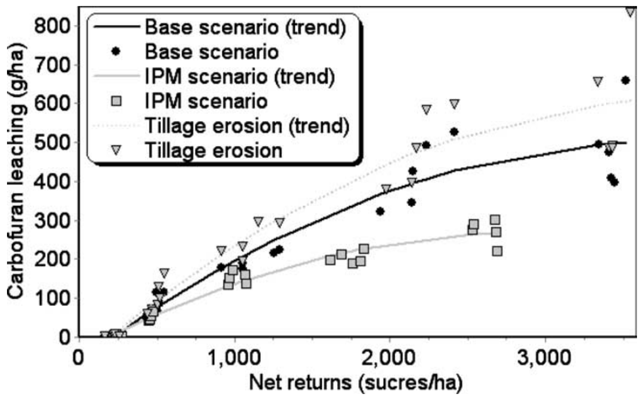

Fig. 8. The effect of IPM and tillage erosion on the tradeoff curve (1800 Sucre ≈ 1 US$).

In this analysis, we first translate the effects of farmers using the IPM technology into changes in the model parameters. The parameter changes can be based on various types of information, including the results of field experiments, experience in other regions, or expert judgment. Use of IPM practices may, for example, result in a lower probability that carbofuran will be applied by farmers at a certain crop development stage (for the example set at 50%). In addition, only a certain percentage of the farmers may actually adopt the alternative technology (set at 80%). Fig. 8 shows the implication of the alternative IPM technology on the tradeoff curve. In this case IPM provides a more effective policy solution than simply taxing potato production. Less income is sacrificed for a greater reduction in leaching by jumping from one curve to another than by moving along the original curve.

Another type of scenario that can be analyzed using the Tradeoff Analysis Model is a natural or human-induced change in the bio-physical environment, such as climate change or the effects of soil degradation. For example, tillage erosion may lead to lower productivities of farmers' fields and, in addition, to an increase in pesticide leaching due to a reduction of the pesticide retention capacity of the soil. These resource changes can also be represented through changes in model parameters, and the effects on sustainability indicators can be shown as a shift in the corresponding tradeoff curve as in Fig. 8. In this example, research organizations and policy makers could use this information to assess whether the adverse impacts of tillage erosion on farm incomes and on environmental processes such as pesticide leaching warrant investments in alternative technologies that reduce tillage erosion.

5. Discussion

The tradeoff analysis model provides an operational tool to quantify economic, environmental, and health tradeoffs. Crissman et al. (1998a) describe in detail the first application of the tradeoff analysis method in Carchi, Ecuador. Implementing the analysis with linked disciplinary data and models was difficult and time consuming, and as a result only a limited number of tradeoff definitions and scenarios could be analyzed within a reasonable time.

A variety of production modeling approaches have been used in integrated assessment research. One approach utilizes representative farm programming models to estimate optimal resource allocations (Kruseman and Bade, 1998). The reliance on the representative farm construct limits their usefulness for explaining spatial variation in economic behavior and linking that behavior to spatially explicit bio-physical process models. A second class of production models is based on econometric models that explain observed outcomes, such as land use or net returns, as reduced form functions of economic variables (input and output prices) and biophysical characteristics of land units (e.g., Mendelsohn et al., 1994). These reduced-form models do not explicitly represent the relationship between productivity and the physical environment. Therefore, they cannot be linked to bio-physical process models of crop and livestock production. A third type of model is based on econometric methods to estimate neoclassical production, cost, or profit functions. These models can be estimated and simulated with site-specific data and thus can be used to represent spatial variation in both bio-physical conditions and economic behavior. They also can explicitly represent the impacts of bio-physical conditions on productivity. However, the parameters of econometric models can only represent the range of behavior observed within the spatial and temporal dimensions of the data used for their estimations. In the econometric-process simulation approach, the linkage of bio-physical crop models with econometric models on a site-specific basis, and the use of these models to characterize the discrete land use and continuous input use decisions of farmers, allow this type of model to predict better outside the range of observed behavior than conventional programming or econometric models.

To implement the econometric-process simulation model, input and output prices and crop output are specified as random variables and introduce spatial and temporal variation in behavior in addition to the effects of bio-physical variation. As such, the econometric-process simulation model differs fundamentally from a deterministic optimization model (e.g., a linear or non-linear programming model) in the way that land allocation decisions are represented. Antle and Capalbo (2001a) argue that this type of stochastic representation provides a more realistic representation of the spatial distribution of land use than the optimization models typically used by agricultural economists. In a deterministic optimization model, expected returns are compared for alternative activities as functions of prices, technology parameters, and resource constraints. The same economically optimal activity is attributed to all fields that are represented by a given parameterization of the model, hence, the same decisions are attributed to these fields with probability one. In the econometric-process model, economic decisions are based on the spatial and temporal distributions of expected returns associated with each alternative land use or input choice. There is a positive probability that each feasible activity will be selected at each field. Thus, as repeated draws are made from the underlying statistical distributions, a realistic spatial and temporal distribution of competing activities is obtained. Outcomes such as corner solutions can only be obtained as a limiting case in which one activity economically dominates other activities at all fields or all time periods.

The Tradeoff Analysis Model was developed to facilitate the interactive process with stakeholders described in Fig. 1. The case study from Ecuador illustrates how the model can be applied and demonstrates the important interactions between biophysical and economic processes in agricultural production systems. One could argue that the quantitative analysis needed to support the tradeoff analysis process should be carried out using one large model. We do not believe that such approach is useful, given the state of science, because no one model can effectively deal with the wide variety of production systems that exist around the world. The Tradeoff Analysis Model is based on the view that a modular approach is more useful, because it facilitates adaptation of disciplinary data and models and their integration on a case-by-case basis by a scientific team (Stoorvogel and Antle, 2001). In the case of the crop growth simulation models, the data standards being used in DSSAT makes introduction of new models extremely easy. However, data standards for environmental process models and economic models are still lacking. Consequently the linkage with these models currently takes place on an ad hoc basis. An important topic for future research is the development of data standards for economic and environmental process models that parallel the standards that now exist for crop models.

Although the tradeoff analysis model is an integrated biophysical and economic modeling tool, it should be seen within the context of the process illustrated in Fig. 1. The application of tradeoff analysis model will only be successful if this process is followed. Tradeoff analysis is a strong tool for impact assessment. However, land use is very dynamic and one can question whether intervention is necessary and feasible. Projective models (e.g., De Koning et al., 1999) and exploratory models (Van Ittersum et al., 1998) may provide excellent added value to direct the predictive tradeoff analysis.

The analysis presented in this paper to illustrate the use of tradeoff analysis and the Tradeoff Analysis Model was based on detailed field-scale data collected for the Carchi case study over a period of several years. Yet to be useful to most stakeholders and public policy decision makers, quantitative tools are needed that can be readily applied with readily available data. Thus, another important topic for future research is the development of methods to parameterize and simulate the types of models needed for tradeoff analysis using minimally necessary data.

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References

Antle, J.M., Capalbo, S.M., 2001a. Econometric-process models for integrated assessment of agricultural production systems. American Journal of Agricultural Economics 83 (2), 389–401.

Antle, J.M., Capalbo, S.M., 2001b. Agriculture as a managed ecosystem: implications for econometric analysis of production risk. In: Just, R.E., Pope, R.D. (Eds.), A Comprehensive Assessment of the Role of Risk in US Agriculture. Kluwer Academic Publishers, Boston, pp. 243–264.

Antle, J.M., Capalbo, S.M., Crissman, C.C., 1994. Econometric production models with endogenous input timing: an application to Ecuadorian potato production. Journal of Agricultural and Resource Economics 19, 1–18.

Antle, J.M., Capalbo, S.M., Crissman, C.C., 1998a. Econometric and simulation modeling of the Carchi potato production system. In: Crissman, C.C., Antle, J.M., Capalbo, S.M. (Eds.), Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Boston, pp. 145–180.

Antle, J.M., Capalbo, S.M., Crissman, C.C., 1998b. Tradeoffs in policy analysis: conceptual foundations and disciplinary integration. In: Crissman, C.C., Antle, J.M., Capalbo, S.M. (Eds.), Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Boston, pp. 21–40.

Antle, J.M., Stoorvogel, J.J., 2001. Integrating site-specific biophysical and economic models to assess trade-offs in sustainable land use and soil quality. In: Heerink, N., van Keulen, H., Kuiper, M. (Eds.), Economic Policy and Sustainable Land Use: Recent Advances in Quantitative Analysis for Developing Countries. Physica-Verlag, Heidelberg, New York, pp. 169–182.

Belzer, R.B., 1999. HACCP principles for regulatory analysis. In: Unnevehr, L. (Ed.), The Economics of HACCP: Studies of Costs and Benefits. Eagan Press, St. Paul, MN, See also. Available from <http://www/umass.edu/ne165/haccp1998/haccp_1998.html>.

Bockstaller, C., Girardin, P., van der Verf, H.M., 1997. Use of agro-ecological indicators for the evaluation of farming systems. European Journal of Agronomy 7, 261–270.

Bowen, W., Cabrera, H., Barrera, V., Baigorria, G., 1999. Simulating the response of potato to applied nitrogen. In: CIP Program Report 1997–1998. CIP, Lima, Peru, pp. 381–386.

Crissman, C.C., Antle, J.M., Capalbo, S.M. (Eds.), 1998a. Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Boston, USA, p. 281.

Crissman, C.C., Espinosa, P., Ducrot, C.E.H., Cole, D.C., Carpio, F., 1998b. The case study site: physical, health, and potato farming systems in Carchi province. In: Crissman, C.C., Antle, J.M., Capalbo, S.M. (Eds.), Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Boston, pp. 85–120.

De Koning, G.H.J., Verburg, P.H., Veldkamp, A., Fresco, L.O., 1999. Multi-scale modelling of land use change dynamics in Ecuador. Agricultural Systems 61, 77–93.

Dercon, G., 2001. Tillage erosion assessment in the Austro Ecuatoriano. Ph.D. Thesis. Catholic University, Leuven, Belgium.

Farrow, A., Winograd, M., 2001. Land use modeling at the regional scale: and input to rural sustainability indicators for Central America. Agricultural Ecosystems and Environment 85, 249–268.

Hansen, J.W., Jones, J.W., 2000. Scaling-up crop models for climate variability applications. Agricultural Systems 65, 43–72.

Jones, J.W., Tsuji, G., Hoogenboom, G., Hunt, L.A., Thornton, P.K., Wilkens, P.W., Imamura, D.T., Bowen, W.T., Singh, U., 1998. Decision support system for agrotechnology transfer: DSSAT v3. In: Tsuji, G.Y., Hoogenboom, G., Thornton, P.K. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 157–177.

Just, R.E., Zilberman, D., Hochman, E., 1983. Estimation of multicrop production functions. American Journal of Agricultural Economics 65, 770–780.

Kruseman, G., Bade, J., 1998. Agrarian policies for sustainable land use: bio-economic modelling to assess the effectiveness of policy instruments. Agricultural Systems 58, 465–481.

Mendelsohn, R., Nordhaus, W.D., Shaw, D., 1994. The impact of global warming on agriculture: a ricardian analysis. American Economic Review 84, 753–771.

Ministerio de Agricultura y Ganaderia (MAG), Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM), 1980. Mapas de Suelos. MAG-ORSTROM, Quito, Ecuador.

Pieri, C., Dumanski J., Hamblin, A., Young A., 1995. Land Quality Indicators. World Bank Discussion Papers #315, The World Bank, Washington, D.C., USA.

Portney, P.R., 1994. The contingent valuation debate: why economists should care. Journal of Economic Perspectives 8 (4), 3–17.

Ritchie, J.T., Griffin, T.S., Johnson, B.S., 1995. SUBSTOR: functional model of potato growth, development and yield. In: Kabat, P., Marshall, B., van den Broek, B.J., Vos, A., van Keulen, H. (Eds.), Modelling and Parametrization of the Soil–Plant–Atmosphere System. Wageningen Pers, Wageningen, The Netherlands, pp. 401–435.

Sands, G.R., Podmore, T.H., 2000. A generalized environmental sustainability index for agricultural systems. Agricultural, Ecosystems, and Environment 79, 29–41.

Smyth, A.J., Dumanski, J., 1993. FESLM: an international framework for evaluating sustainable land management. World Soil Resources Report 73. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Stoorvogel, J.J., Antle, J.M., 2001. Regional land use analysis: the development of operational tools. Agricultural Systems 70, 623–640.

Stoorvogel, J.J, Antle, J.M., Crissman, C.C., Bowen, W., 2001. The Tradeoff Analysis Model Version 3.1: A Policy Decision Support System for Agriculture (User Guide). Laboratory of Soil Science and Geology, Wageningen University, The Netherlands.

Stoorvogel, J.J., Jaramillo, R., Merino, R., Kosten, S., 2003. Plaguicidas en el medio ambiente. In: Yanggen, D., Crissman, C., Espinosa, P. (Eds.), Los plaguicidas: impactos en producción, salud y medio ambiente en Carchi. CIP, INIAP, Quito, Ecuador, pp. 49–69.

Tiktak, A., van den Berg, F., Boesten, J.J.T.I., van Kraalingen, D., Leistra, M., van der Linden, A.M.A., 2000. Manual of FOCUS PEARL version 1.1.1. RIVM Report 711401008, Alterra Report 28. National Institute of Public Health and the Environment, Bilthoven, The Netherlands.

Turkelboom, F., Poesen, J., Ohler, I., Ongprasert, S., 1999. Reassessment of tillage erosion rates by manual illage on steep slopes in Northern Thailand. Soil and Tillage Research 51, 245–259.

Van Alphen, B.J., Stoorvogel, J.J., 2000. A functional approach to soil characterization in support to precision agriculture. Soil Science Society of America Journal 64, 1706–1713.

Van Alphen, B.J., Stoorvogel, J.J., 2002. Effects of soil variability and weather conditions on pesticide leaching – a farm-level evaluation. Journal of Environmental Quality 31, 797–805.

Van Ittersum, M.K., Rabbinge, R., Van Latesteijn, H.C., 1998. Exploratory land use studies and their role in strategic policy making. Agricultural Systems 58, 309–330.

Van der Werf, H.M.G., Petit, J., 2002. Evaluation of the environmental impact of agriculture at the farm level: a comparison and evaluation of 12 indicator-based methods. Agriculture, Ecosystem, and Environment 93, 131–145.

Varian, H.R., 1992. Microeconomic Analysis. W.W. Norton Company, New York.

Veen, M., 1999. Land use and its effects upon soil development: a study in the potato production area around San Gabriel, Carchi. MSc Thesis. Department of Soil Science and Geology, Wageningen Agricultural University, Wageningen, The Netherlands.

Wagenet, R.J., Bouma, J., Hutson, J.L., 1998. Conceptual and methodological aspects of assessing pesticide environmental impact in developing areas. In: Crissman, C.C., Antle, J.M., Capalbo, S.M. (Eds.), Economic, Environmental, and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Kluwer Academic Publishers, Boston, pp. 41–63.

World Commission on Environment and Development (WCED), 1987. Our Common Future. Oxford University Press, Oxford, UK.