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Trade-off analysis in the Northern Andes to study the dynamics in agricultural land use

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Abstract

In this paper we hypothesize that land use change can be induced by non-linearities and thresholds in production systems that impact farmers' decision making. Tradeoffs between environmental and economic indicators is a useful way to represent dynamic properties of agricultural systems. The Tradeoff Analysis (TOA) System is software designed to implement the integrated analysis of tradeoffs in agricultural systems. The TOA methodology is based on spatially explicit econometric simulation models linked to spatially referenced bio-physical simulation models to simulate land use and input decisions. The methodology has been applied for the potato-pasture production system in the Ecuadorian Andes. The land use change literature often describes non-linearity in land use change as a result of sudden changes in the political (e.g. new agricultural policies) or environmental setting (e.g. earthquakes). However, less attention has been paid to the non-linearities in production systems and their consequences for land use change. In this paper, we use the TOA system to study agricultural land use dynamics and to find the underlying processes for non-linearities. Results show that the sources of non-linearities are in the properties of bio-physical processes and in the decision making-process of farmers.

Keywords: Tradeoff analysis; Agricultural land use change; Ecuador

1. Introduction

The agricultural sector has to deal with rapidly increasing population pressures, with highly dynamic world markets, with a changing biophysical environment through land degradation and climate change, with rapid technological advancements, and with many changes in the political arena through, e.g. the introduction of structural adjustment programs. All these factors influence, directly or indirectly, the land allocation and land management decisions by farmers. As a result, land use is highly dynamic and rarely reaches equilibrium. Despite the complexity and variability of land use change, it is extremely important to get insight in possible trajectories of land use change and the driving factors behind these changes. Only then can we evaluate the need for intervention and the feasibility and impact of new agricultural technologies and policies. This explains the increasing research activities in the field of land use and land cover change (Veldkamp and Lambin, 2001).

Land use data often show that changes do not occur linearly but gradual changes are punctuated with rapid changes. In some cases, these rapid changes may occur as a result of easily explainable factors like the introduction of certain agricultural policies, technological innovations or natural disasters. In other cases, however, these changes and their causes are not obvious. Reasons can be found in, e.g. gradual changes in soil quality as a result of soil degradation or prices. Non-linear relationships between, e.g. soil quality and crop choice may subsequently cause a rapid change in land use patterns. In this paper we will study the relationships and thresholds in production systems that may lead to non-linear or abrupt changes in agricultural land use by impacting the decision making processes of farmers.

Different tools have been developed to analyze land use dynamics varying from statistical approaches to

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mathematical programming models (Veldkamp and Lambin, 2001). The approaches vary in the basic techniques, assumptions and the spatial and temporal scales they operate on. The Tradeoff Analysis (TOA) System (Stoorvogel et al., 2001, 2004) is one of the models for the analysis of land use dynamics. The TOA system is based on a spatially explicit econometric simulation model estimated on observed decision making of a population of farmers. The system integrates this econometric simulation model with a crop growth simulation model to indicate the production potential of a particular field and environmental impact models for the evaluation of management decisions. We will show in this paper that this integration makes the system very suitable for our objectives, i.e. the analysis of non-linearities and thresholds behind land use change.

We will focus on agricultural land use in the potato-pasture system in Northern Ecuador. In this area, the clash between agricultural and environmental goals engenders conflicting agricultural, environmental, research, and development policies directed toward agriculture and natural resources. Agricultural and environmental policies available to governments generally fall into two categories: regulations and incentives (Just and Antle, 1990). In general, in developing countries such as Ecuador, regulations have minimal effect due to the lack of monitoring and enforcement capacity in the government. This leaves policies that provide incentives to change behavior. Compared to regulations, incentive policies, which include taxes and subsidies, are more difficult to target to particular areas or situations. Therefore, there is a need for an *ex ante* analysis to determine the effect of incentive policies on the tradeoff.

2. Materials and methods

2.1. The potato-pasture system

The agricultural system in Carchi Province in Northern Ecuador is dominated by a rotation of pasture (mainly for the production of milk) and potatoes on the steep Andean hillsides. The research focused on two watersheds encompassing a total area of approximately 95 km^2 ranging in altitude between 2700 and 3800 m above sea level (Fig. 1). 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 (Fig. 1). Crissman et al. (1998) give a full description of the Carchi study site and the data set used in this analysis.

The intensive, commercial production of potatoes results in a number of environmental threats. Intensive mechanized tillage for land preparation and harvesting has lead to tillage erosion on steeply sloped fields. In many cases the light colored sub-soils are exposed on the higher parts of the fields as a result of this erosion (Veen, 1999; Dercon, 2001). Secondly, intensive potato production is associated with heavy use of agrochemicals (Yanggen et al., 2002). Although rainfall intensities are low and topsoils are rich in organic matter leading to high pesticide retention, pesticide leaching is occurring in fields where tillage erosion has removed the topsoil or with heavy pesticide

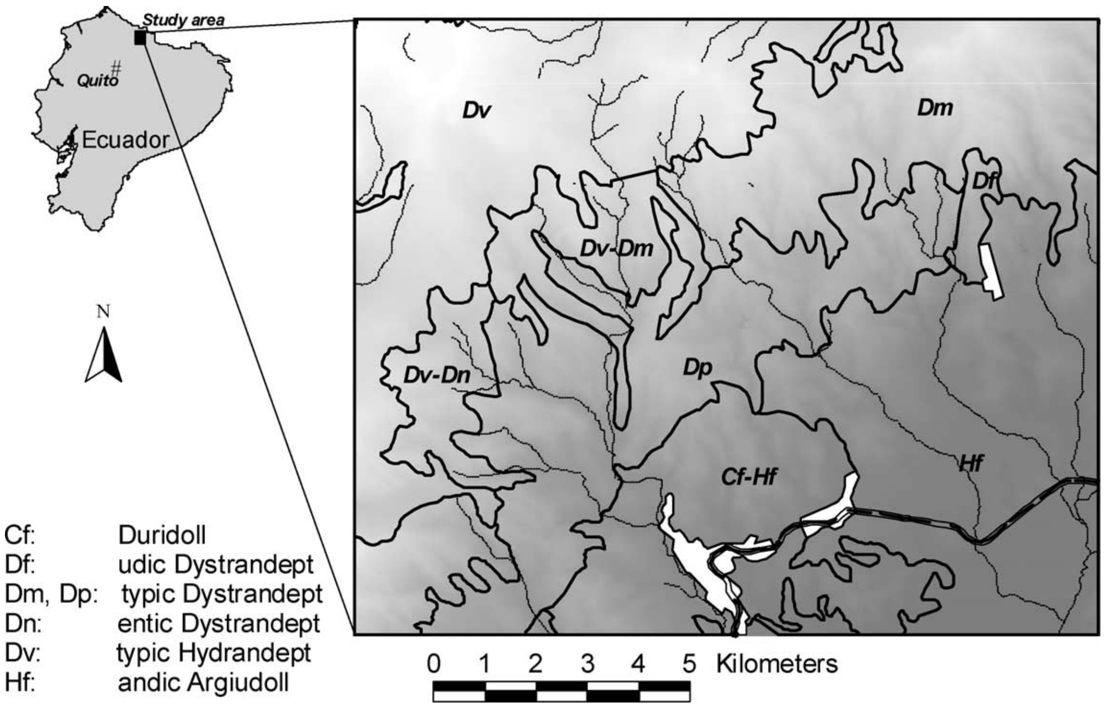

Fig. 1. Location of the study area and the distribution of the major soil types (MAG and ORSTOM, 1980).

use (Stoorvogel et al., 2002). Intensive pesticide use has also resulted in serious human health risks due to improper application techniques (Cole and Mera-Orcés, 2003). In this paper, we will specifically focus on the environmental impacts in terms of tillage erosion and carbofuran leaching. Carbofuran was identified as among those pesticides 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.[1] Farmers apply on average 1.3 kg Carbofuran/ha on their potato crops.

Agriculture in the study area has been characterized by a 2-year dynamic survey in 1991–1992 including 40 farms with a total of 187 agricultural fields. This survey includes detailed registration of agricultural management and production together with economic data on agricultural management (Crissman et al., 1998).

2.2. The decision making process

Land use change can only be studied through a multi-scale analysis where at different scale levels different drivers may play an important role (De Koning et al., 1999). However, ultimately it is the farmer who makes decisions at the field level in terms of crop choice and crop management. These decisions are constrained at the farm level by the availability of resources (e.g. labour) and they are driven by farmers' objectives in terms of, e.g. profit, self-sufficiency and food security (Vanacker et al., 2003). All these decisions are taken within a higher-scale context of markets and policies. An important driving factor behind farmers' decisions is the output they expect to obtain in the growing season. This output is a function of inherent land qualities (including soil and climate) and current agricultural practices. It is this relationship between land quality and farmers' decision-making where land degradation plays an essential role. Farmers' decisions may result in non-sustainable management practices that lead to land degradation, particularly in those cases such as gradual loss of top soil and soil fertility where it is difficult for farmers to perceive short-run changes. Over time soil degradation results in a decline of land quality that influences farmers' decision in terms of land allocation and land management.

At the same time there are important environmental effects that do not directly impact land productivity at the farm level. For example, pesticide leaching may impact the environment, but these effects will be principally off-farm and only have impact on farm management through specific legislation.

[1] www.who.int/pcs/docs/Classification of Pesticides 2000-01.pdf

2.3. The tradeoff analysis system

The TOA system is developed to simulate the complex interactions between economic and environmental factors of agricultural systems. Economics teach us that in every decision and every choice there is a tradeoff between benefits and costs. Along with the obvious benefit of food production, the cost of agriculture can include adverse effects on the environment and human health. Implicitly we use tradeoff curves every day in all our decisions. The tradeoff curve is simply a concrete expression of what is usually a mental calculation. For example, politicians or analysts can readily see if the sacrifice of a single unit of environmental quality will result in a gain of a single unit or five units of agricultural production. Politically determined weights would then guide the decision as to whether the size of sacrifice is acceptable.

The TOA System (Stoorvogel et al., 2001, 2004) is designed to implement the integrated analysis of tradeoffs between different sustainability indicators dealing with the, e.g. economic, environmental and health effects of agricultural systems. This analysis is based on econometric production functions. These functions are estimated on the basis of observed decision making in the dynamic farm survey. Production economists typically specify these production functions in the general form $q = f(\mathbf{x}, \mathbf{z}, \mathbf{e})$ where $\mathbf{x}$ 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 TOA system takes 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 $q = g(\mathbf{x}, \mathbf{e})$. Defining average or expected input use as $\mathbf{x}^*$, 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 as $q^* = g(\mathbf{x}^*, \mathbf{e})$. We can now replace the vector $\mathbf{e}$ in the production function with the newly calculated inherent productivity: $q = h(\mathbf{x}, \mathbf{z}, q^*)$. Substituting for q^* we obtain $q = h(\mathbf{x}, \mathbf{z}, g(\mathbf{x}^*, \mathbf{e}))$, showing that this procedure yields a special case of the production function $q = f(\mathbf{x}, \mathbf{z}, \mathbf{e})$ in which the biophysical variables $\mathbf{e}$ are weakly separable from the variable and fixed inputs $\mathbf{x}$ and $\mathbf{z}$. Thus, the bio-physical crop 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. This now allows the production functions to simulate the relationship between land quality and management decisions by the farmer. The TOA system goes one step further and includes also environmental impact models. This allows the estimation of the change in soil quality and as a result the change in productivity. Now we can study the feed-backs of management practices on future agricultural decision making through the analysis of changes in soil quality.

All models have been developed after intensive data collection in the study area. A 2-year dynamic survey provided information about the way farmers take decisions. This survey was the basis for the development of an economic-process simulation model for the two watersheds. Within the context of this paper we assume the production function for each production activity to be non-joint in inputs following Just et al. (1983). The economic simulation model is estimated on the basis of survey data to reflect actual decision-making in the study area. Details of the economic simulation model are described by Antle et al. (1998) and Antle and Capalbo (2001).

The inherent productivity of potatoes is simulated using a calibrated version of the SUBSTOR model (Ritchie et al., 1995). SUBSTOR was calibrated using existing potato experiments and a limited number of additional field experiments (Bowen et al., 1999). Tillage erosion was modeled statistically on the basis of an analysis of 48 fields where land use history as well as detailed transects through the fields describing soil movement were analyzed (Veen, 1998). Additional experiments on soil movement as a result of tillage (following Dercon, 2001) were carried out on a few fields to check the statistical model. Carbofuran leaching was modeled based on the LEACHP model (Wagenet and Hutson, 1989). Additional field experimentation revealed site-specific data on pesticide degradation and sorption (Stoorvogel et al., 2003).

The basic structure of the TOA model is summarized in Fig. 2. First, crop growth models (specifically, models using the DSSAT input and output format, see Jones et al., 1998) are used to characterize spatial variability in productivity across sites. Second, the econometric-process simulation model determines land use and input use for a specified number of cropping cycles. Each cropping cycle, prices are sampled from prices distributions reflecting observed distributions of farm gate prices that may be perturbed in scenario analysis. Third, land allocation and input use are passed to environmental process models (such as LEACHP, WEPP, Century, etc.) to simulate environmental impacts of management decisions. Subsequently, the results of the environmental-process models may influence the environmental characteristics of the fields.

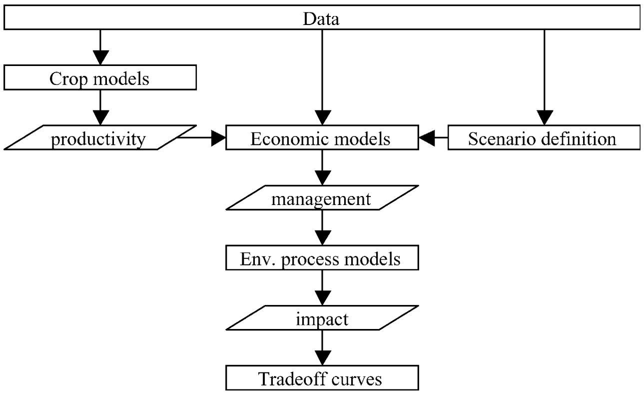

Fig. 2. The basic structure of the Tradeoff Analysis Model.

2.4. Analyzing environmental quality and land use dynamics

To analyze the complex relationships between agricultural development and land degradation we will construct pair-wise tradeoffs among:

- net returns,[2]
- crop allocation in terms of the ratio between potato production and pasture in the crop rotation,
- crop management in terms of carbofuran usage, and
- environmental impact in terms carbofuran leaching.

As a starting point we look at the joint distribution of these indicators. All simulation runs include 25 crop cycles for 100 fields randomly located throughout the watersheds.

Tillage erosion is one of the important processes that will influence future management decisions. The basis for these changes can be found in the impact of tillage erosion on land productivity as a result of changes in soil depth. The crop growth simulation model SUBSTOR allows us to study the impact of changes in soil depth on the inherent productivity. Veen (1998) analyzed 48 soil profiles and showed that the process of tillage erosion is a linear process in which topsoil material is removed from the upper part of the field. A similar amount of material is subsequently deposited in the lower part of the field. Here we express the degree of tillage erosion as the difference in the thickness of the topsoil between the upper and lower part of the field (d in cm). The basic assumption underlying this calculation is that fields without tillage erosion exhibit a uniform thickness of the topsoil. The corresponding inherent productivity of a field with a tillage erosion of d cm is calculated as the average of three locations: the lower part of the field with $0.5 \cdot d$ cm increase in topsoil, the middle part of the field with no change in topsoil, and the upper part of the field where $0.5 \cdot d$ cm topsoil (or in extreme cases even some subsoil) is removed. This allows us to transfer the relations between soil thickness and inherent productivity into a relationship between tillage erosion and inherent productivity. Subsequently the TOA system can be used to analyse the relationship between inherent productivity and key indicators for land management.

[2] To value net returns we will use Ecuadorian sucres. The exchange rate during this study varied highly. The average exchange rate was 1000 sucres per US dollar.

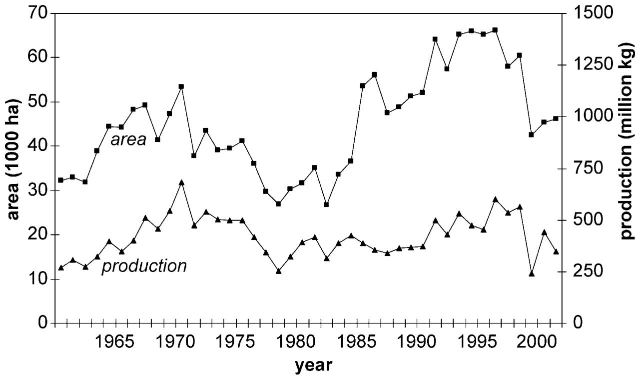

Fig. 3. Dynamics in the total potato area and the total potato production in Ecuador (FAO, 2003).

The inherent productivity is only one of many factors driving management decisions. Another important driving factor for land management is the constantly changing potato price. Historical data show that potato prices fluctuate significantly. We will vary the level of the potato price between 50 and 150% of the observed data and study the impact on land management. The survey data showed that farmers experience very different input and output prices. The economic-simulation model draws from the observed distribution of prices at the beginning of each crop cycle. Changes in potato prices are imposed on the model by shifting the mean of the distribution while holding the standard deviation constant.

One of the sources of variation in agricultural management is the variability in soil and climatic conditions throughout the watersheds. It can therefore be expected that different parts of the watershed will react differently to the changes in potato prices. This can be illustrated by interpolating the results obtained for the individual fields. Average results obtained for the 100 fields under different price scenarios are interpolated using ordinary kriging (Journel and Huybregts, 1978).

The site-specificity of land use dynamics can also be shown by a TOA for four different soil types that vary in the depth of the topsoil and the level of tillage erosion. Tillage erosion will change the soil properties affecting the inherent productivity and as a result crop management. In addition to causing changes in the inherent productivity, tillage erosion will result in an increase in the risk for pesticide leaching. Changes in land management and the risk for pesticide leaching result in a combined effect on carbofuran leaching over time.

3. Calculation

A simple look at the FAO production figures shows the large variation in potato production and area during the last four decades for Ecuador (Fig. 3). The sources of this variation can be found in the usual climatic and market effects as well as in some significant exogenous shocks. One such example comes from 1999 when Ecuador experienced a high rate of inflation that led to the decision to abandon the Ecuadorian sucre and introduce the US dollar as the national currency. The direct effect of dollarization for farmers was the increase in prices of imported inputs such as pesticides. At the national level the area under potato declined from 60,000 to almost 40,000 ha. Carchi province followed the same trend. Farmers focused much more on the production of milk that requires less expensive external inputs.

The above example is illustrative for the results we see with the TOA model. Fig. 4 shows the results of an analysis for 100 randomly selected fields throughout the two catchments. One can observe a positive relationship between the net returns and the ratio of potato and dairy production in the crop rotation. It clearly shows that potatoes are the more profitable enterprise. At the same time, we observe an increase in the application of Carbofuran, an insecticide being used only in the potato

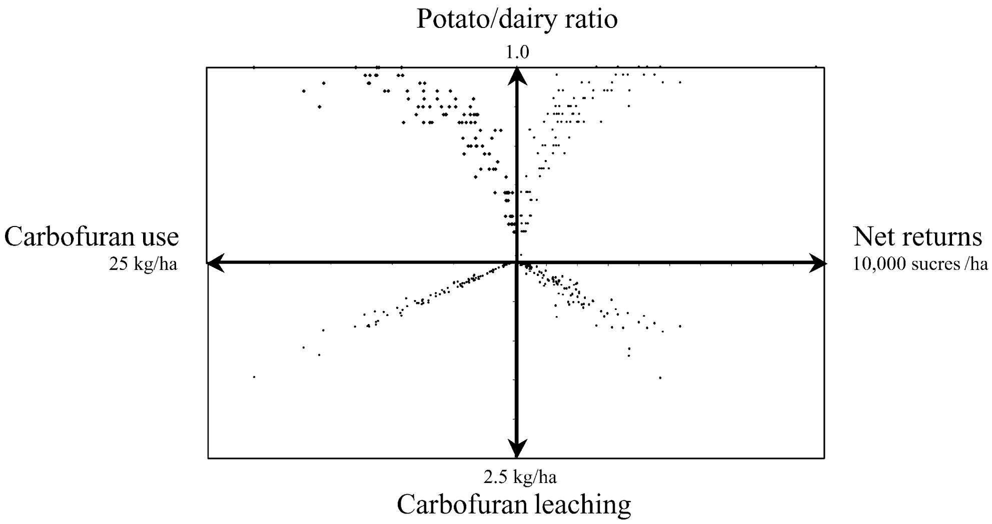

Fig. 4. The interrelationships between 4 simulated sustainability indicators for the Carchí study area.

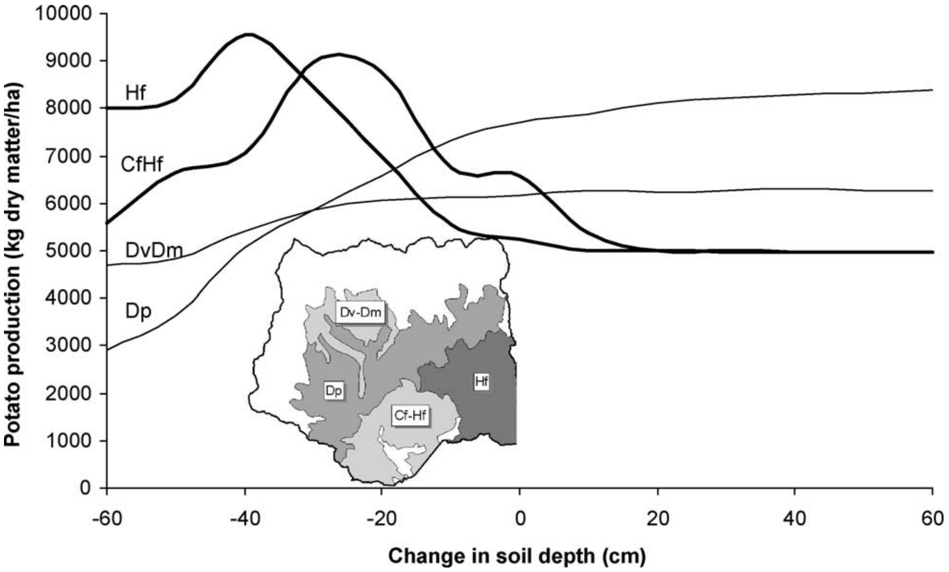

Fig. 5. The effect of soil depth on the simulated inherent potato production for four soil types in the Carchí study area.

crop. Despite soil and climatic differences in the study area one can observe an almost linear relationship between Carbofuran use and Carbofuran leaching. The leaching results integrate the other relationships shown in Fig. 4. The increase in leaching is due to two factors: first, as potato prices increase farmers dedicate more land to potato and because carbofuran use reduces crop losses; and second, farmers use more carbofuran on the potatoes that are planted. Thus both land use and crop management decisions are captured in the results in the southeast quadrant.

The relationships illustrated in Fig. 4 will change over time because of tillage erosion under the potato/pasture rotation. These changes are reflected in the risk for Carbofuran leaching and also result in changes in crop management. As discussed Section 2.4, the inherent productivity of a parcel of land will change the crop choice and crop management decisions. The SUBSTOR model allows us to explore the impact of changes in soil depth on the inherent productivity. Fig. 5 shows the results of such an analysis for the four principal soil types in the Carchi study area. Two soil types (Dp and Dv–Dm) in the upper northwestern part of the watersheds behave as one would expect. A decrease in the topsoil depth results in a significant decrease in the inherent productivity. However, the addition of topsoil material has no major impact on these relatively deep and fertile soils. The two other soil types (Cf-Hf and Hf) in the lower part of the watershed behave differently. A decline in soil depth has a positive effect on productivity (potato dry matter yield). This increase in productivity is the result of the high water holding capacity of the deeper soil horizons, especially in the lower part of the watershed. The lower watershed receives on average 500 mm of rain per year less than the upper part where total annual rainfall reaches almost 1500 mm per year. Probably also as a result of the dryer conditions in the lower part of the watershed, the topsoils may have a lower water holding capacity as a result of irreversible drying of the volcanic material (Shoji et al., 1993). The relatively low water holding capacity of the topsoil in combination with a more water constrained agricultural production results in an initial positive effect of tillage erosion.

We can derive the impact of tillage erosion on the inherent productivity from Fig. 5. The results are shown in Fig. 6. Tillage erosion rates under certain conditions (slopes around 14%, potato cultivation, and tractor plowing up and down slope) move around 5 cm of soil per cropping cycle (including multiple tillage operations). Not surprisingly the SUBSTOR model predicts declining productivity with increasing erosion for most soil groups. The exceptions once again are the Hf soils in the lower watershed where water retention plays an important role.

To interpret these SUBSTOR inherent productivity results in the context of land use change it is important to analyze the effect of these changes on crop rotation and on crop management. To carry out this analysis the economic simulation model was run 500 times for

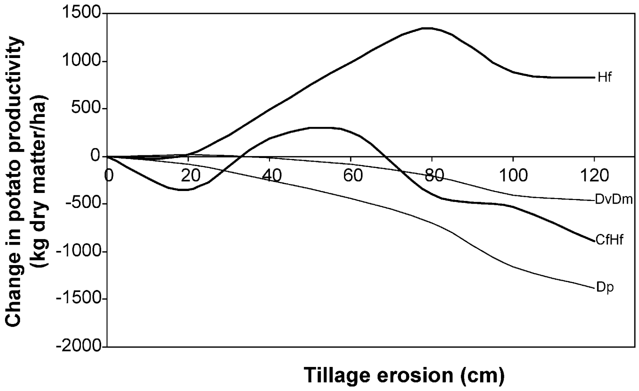

Fig. 6. The effect of tillage erosion on the inherent potato production for four soil types in the Carchí study area.

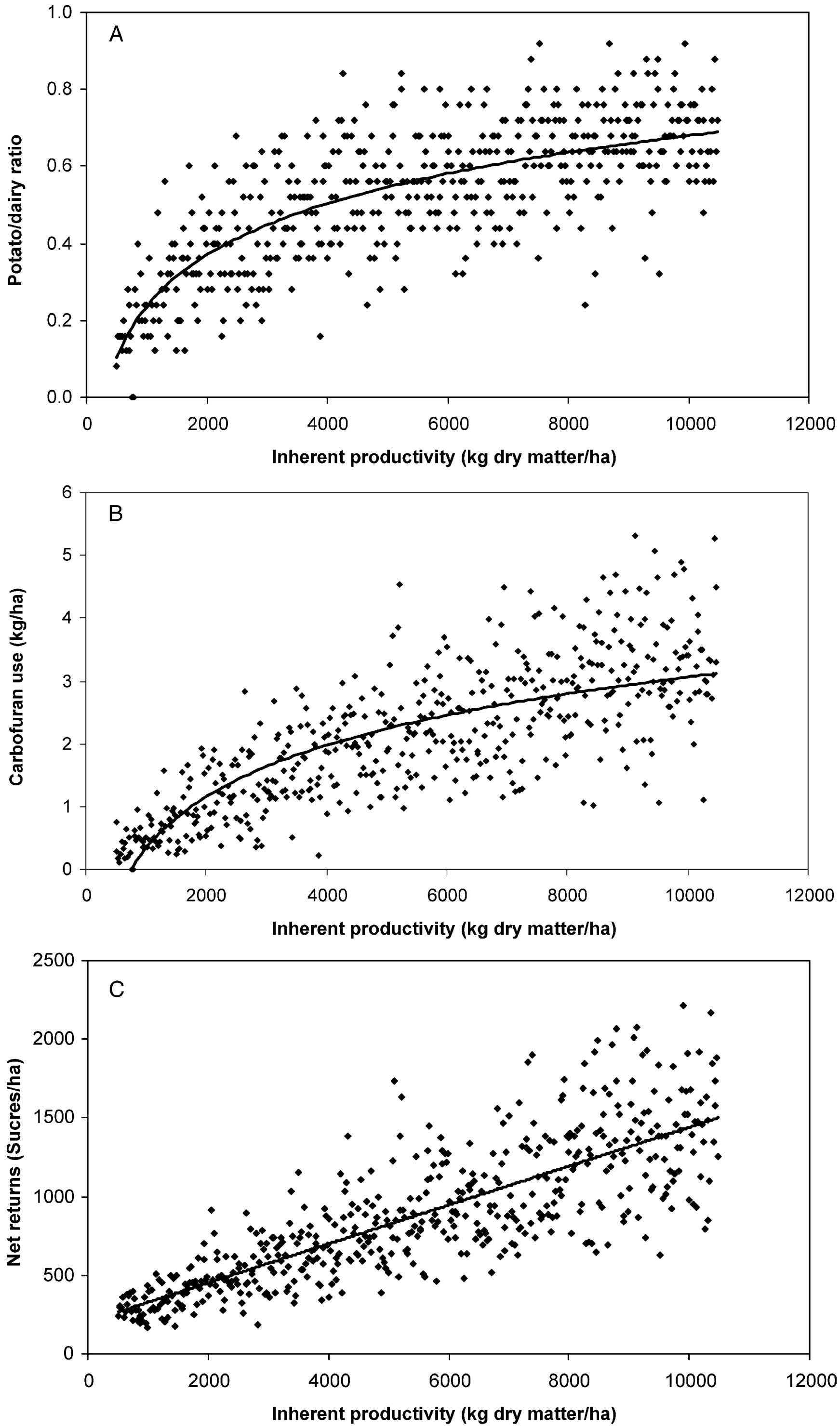

Fig. 7. The effect of changes in the inherent productivity on crop management expressed as the ratio between potato and pasture in the crop rotation (A), the usage of Carbofuran (B), and the net returns (C).

different levels of the inherent productivity. Fig. 7 shows the effect of changes in the inherent productivity on the crop rotation, Carbofuran use and net returns. Not surprisingly, better soils confer improved yield to potato. As potato yields increase the farmers dedicate more land to potato (panel A), use more carbofuran (panel B) and make more money (panel C). The impact changes in the inherent productivity clearly depends on the original level of inherent productivity. Smaller inherent productivities will show a larger impact than larger inherent productivities do. On the other hand we can see that net returns on average have a linear relation with

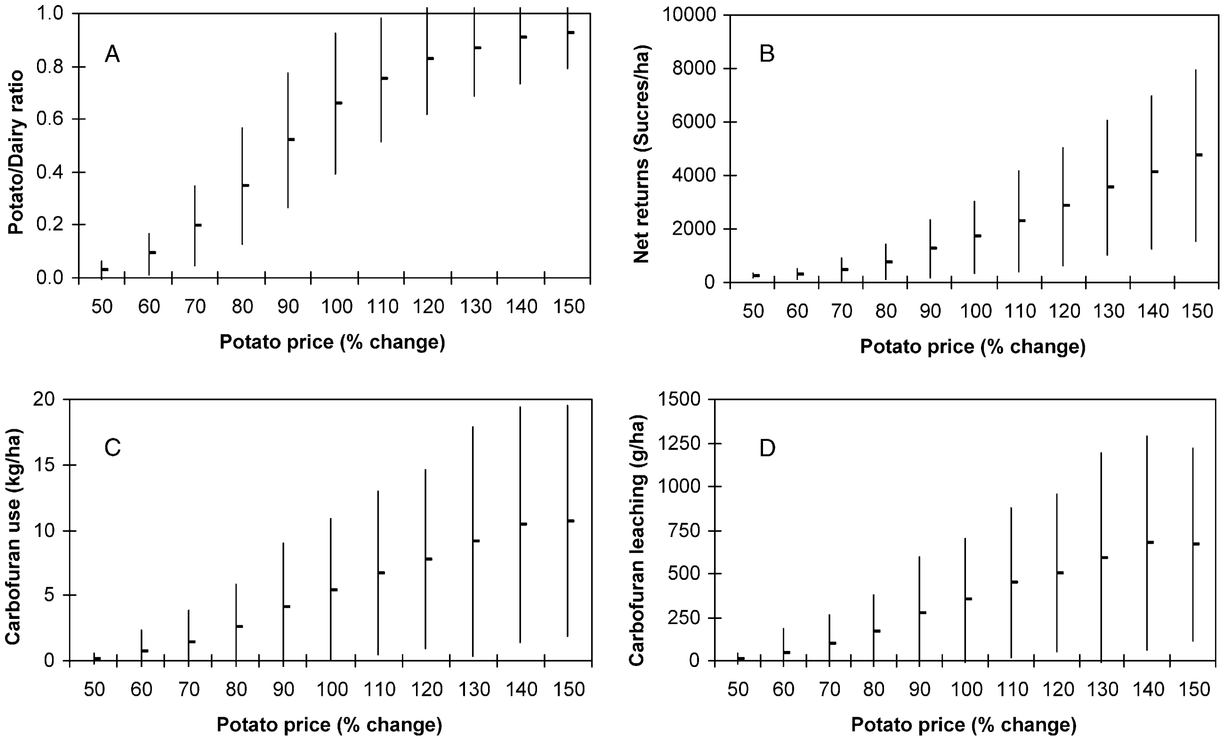

Fig. 8. The effect of changes in the potato prices on crop management expressed as the ratio between potato and pasture in the crop rotation (A), net returns (B), Carbofuran use (C), and Carbofuran leaching (D) and the associated standard deviations.

productivity: a reduction of 1000 kg dry matter/ha costs the farmers approximately 124 sucres/ha.

In addition to the dynamics in the physical system, the variation in the area under potato and its productivity can also be explained by the variation in potato prices farmers expect to receive for their harvest. Prices vary between 50 and 150% of the observed prices. An analysis with the tradeoff model shows that the impact on land management is just as important as differences in the inherent productivities (Fig. 8). When potato prices drop with 50% the crop system shifts completely to dairy production. On the other hand if prices go up by 50% the system shifts to almost exclusively potato. Logically these changes in potato prices result in a direct change in the net returns. With the change in the production system farmers will use more Carbofuran. This increase is not only the result of the increased acreage but with the increasing value of the crop farmers have more interest in the protection of their harvest.

Land use change as a result of increased potato prices is not constant as indicated by the large standard deviations. Part of this variation is expressed by spatial variability in soils and climate that will result in different levels of the inherent productivity. Fig. 9 shows these differences where farmers in the upper and lower parts of the watershed (north-west and south-east) shift more easily into potato when prices go up compared to farmers in the middle area. This spatial variability illustrates that one should take care in the generalization of these results. However, farmers will experience a decline in productivity under continuous cropping with potato as a result of the build up of pests and diseases. Nevertheless, with a sufficiently large increase in potato prices relative to milk, the rotation moves toward higher potato intensity but pasture remains in the rotation to some degree.

Fig. 10 shows that temporal variation is just as important as the spatial variability. Different bio-physical conditions may lead to different rates of tillage erosion and changes in the inherent productivity, management and carbofuran leaching.

4. Discussion

The analysis illustrates the complexity of agricultural systems. All variables considered in this study are closely interrelated. The relationships are in many cases non-linear and site-specific. The impact of tillage erosion on productivity and subsequently on crop management clearly show non-linear behavior. What are the lessons to be learned?

From a research perspective it is important to carefully select the temporal and spatial scales to be examined (Crissman et al., 1998). However, we have to realize that probably in most cases we have to have work at a number of scale levels (Bouma and Droogers, 1999) and include the interactions of the different scale levels (e.g. De Koning et al., 1999). A carefully selected research chain that deals with the different scale levels and their interactions is

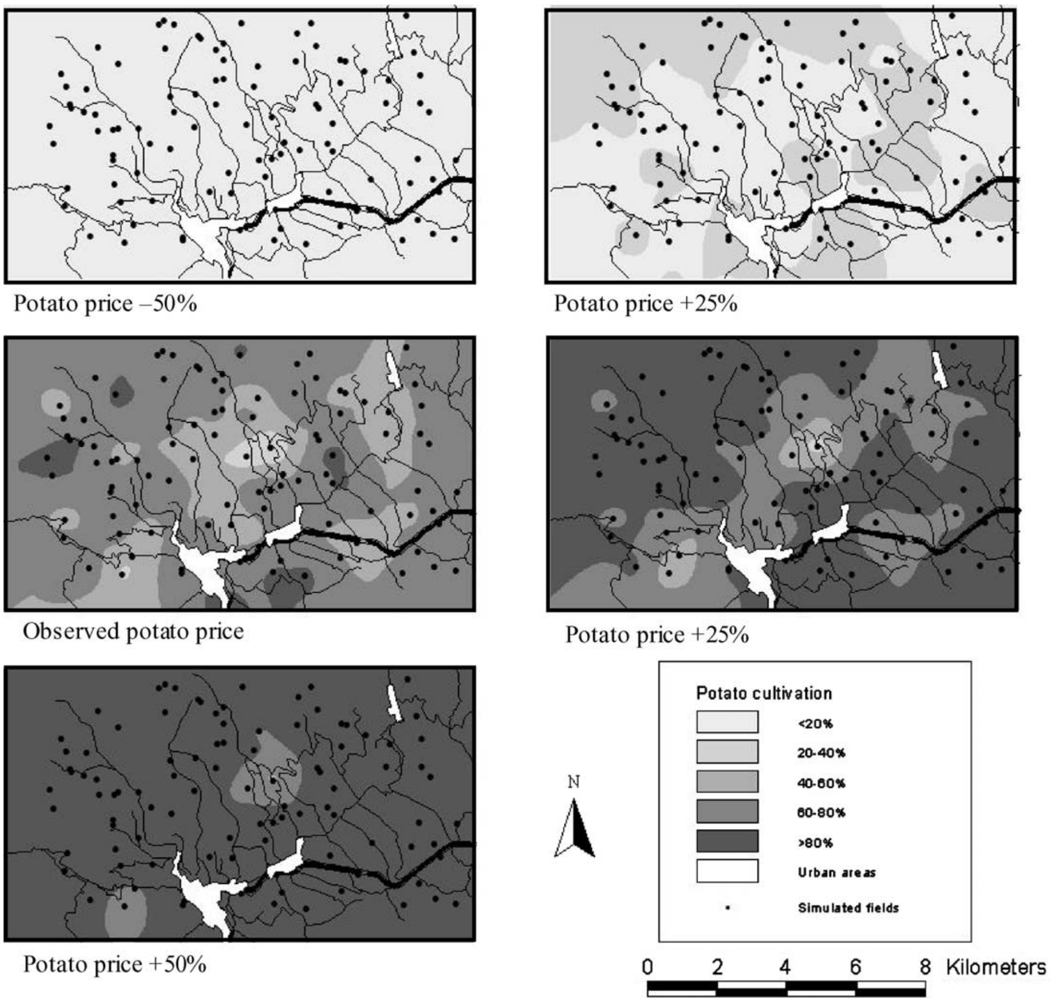

Fig. 9. The spatial variation of the role of potato in the crop rotation under different potato price scenarios.

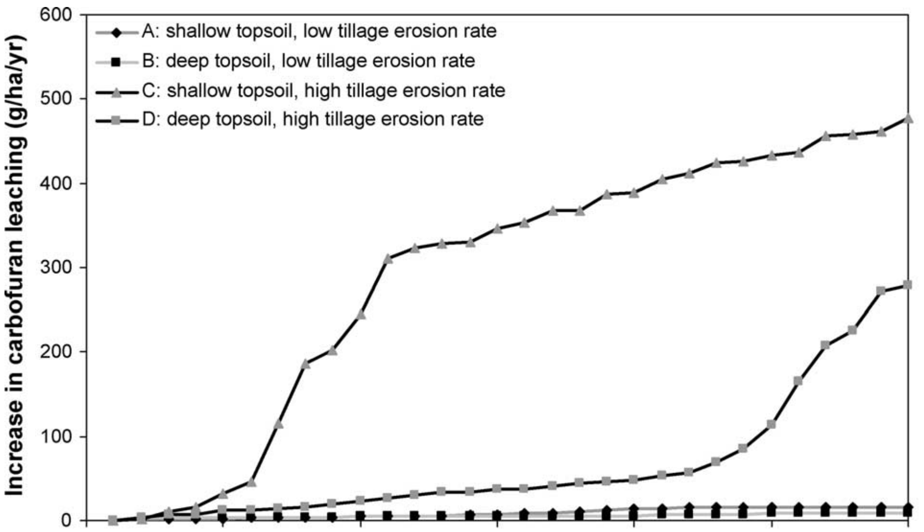

Fig. 10. The temporal dynamics in carbofuran leaching for four different fields as a result of tillage erosion and management changes.

required. This is illustrated in the results. Basic relations between soil depth and potential productivity are translated into an impact assessment of tillage erosion. The subsequent analysis with the economic simulation model permits us to examine land use change as a result of tillage erosion. At the lower scale levels we observe that different soil types do react differently to tillage erosion, and thus have different effects on land management. Soil types with a high inherent productivity show small effects on land use as a result of changes in the inherent productivity in contrast to soil types with a low inherent productivity. However, if we are interested in the net returns then we see that net returns show a linear relationship to changes in the inherent productivity.

The TOA System gives the researcher the capacity to analyze complex interactions between land use change and a range of sustainability indicators. Coupling the models provides the researcher with significant additional analytical power above what would be possible with independent non-coupled models. Too often data are generalized for integrated analysis through, for example, a 'representative farm' typology (e.g. Singh et al., 1986). Other examples are the representative soil type and the representative weather station. Within the TOA System approach, spatial variability embodied in site-specific data is used to characterize heterogeneity in behavior and its environmental consequences. However, this increase in realism comes at a cost, namely the cost of obtaining reliable, spatially explicit data. Especially in the analysis of environmental impacts we often see that small, non-representative areas or hot-spots have large impacts on the environment. These effects can only be demonstrated if the data and models are site specific.

We presented results from a relatively simple production system to illustrate how spatial heterogeneity, non-linearities and thresholds can be illustrated using the tradeoff model. Our ultimate goal is to incorporate the dynamics in these systems, for example, by including feedbacks from the environmental impacts to crop production and farmer decision making.

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