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An interdisciplinary approach to regional land use analysis using GIS, with applications to the Atlantic Zone of Costa Rica

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Abstract

Policy makers and other stakeholders concerned with regional rural development increasingly face the need for instruments that can improve transparency in the policy debate and that enhance understanding of opportunities for and limitations to development. To this end, a methodology called SOLUS (Sustainable Options for Land Use) was developed by an interdisciplinary team of scientists over a 10-year period in the Atlantic Zone of Costa Rica. The main tools of SOLUS include a linear programming (LP) model, two expert systems that define technical coefficients for a large number of production activities, and a geographic information system (GIS). A five-step procedure was developed for GIS to spatially reference biophysical and economic parameters, to create input for the expert systems and the LP model, to store and spatially reference model output data, and to create maps of both model input and output data. SOLUS can be used to evaluate the potential effects of alternative policies and incentive structures on the performance of the agricultural sector. A number of practical applications demonstrate SOLUS's capability to quantify trade-offs between economic objectives (income, employment) and environmental sustainability (soil nutrient balances, pesticide use, greenhouse gas emissions). GIS-created maps visualize the spatial aspects of such trade-offs and indicate hotspots where local goals may conflict with regional goals.

JEL classification: O13; Q18; Q20

Keywords: Costa Rica; GIS; Interdisciplinary; Land use analysis; Linear programming

1. Introduction

Rural development is intrinsically related to the way in which the land is used. Given the rising awareness of the multiple trade-offs involved in decision making regarding the use of available land resources (Griffon et al., 1999; Kuyvenhoven et al., 1995, 1998), policy makers face the increasingly complex task of accommodating multiple objectives of different stakeholders with conflicting interests in regional development. This implies a need for tools that can be employed to

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provide insights into the opportunities and limitations to land use. Such tools should be capable of quantifying trade-offs between socioeconomic, sustainability-related, and environmental policy objectives.

This article presents a methodology called SOLUS (Sustainable Options for Land Use; Bouman et al., 1999; Jansen et al., 2001) that can help in the exploration of the aggregate effects of policy measures and incentives on efficiency as well as noneconomic (i.e., environmental and sustainability) objectives related to land use, including quantification of trade-offs between such objectives. A major challenge in the development of the SOLUS methodology consisted of the integration of biophysical with economic information and models on a geo-referenced basis. SOLUS uses GIS to archive, manage, and calculate geo-referenced data; to link GIS data to models of land use exploration, and to spatially present model results.

The remainder of this article is structured as follows. The next section describes the SOLUS methodology and its various components. Section 3 provides a description of the region where SOLUS was first developed and applied, i.e., the Northern Atlantic Zone (NAZ) of Costa Rica (Fig. 1). The fourth section develops a number of policy-oriented scenarios that serve as an illustration of the application domain of SOLUS. The results of these scenarios are discussed in Section 5. The final section is reserved for conclusions.

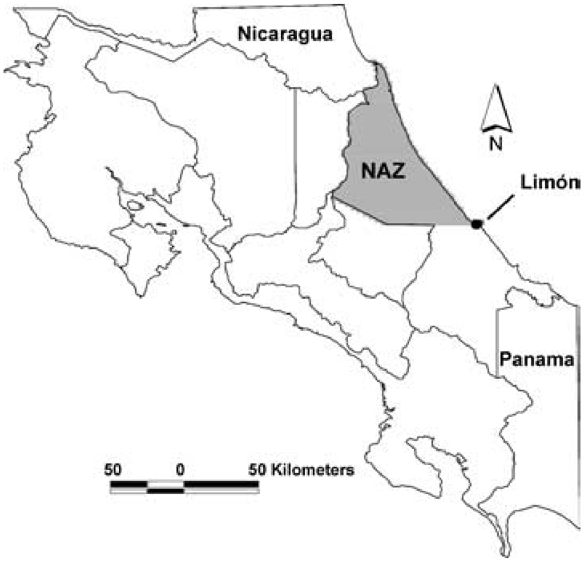

Fig. 1. Case study area: the Atlantic Zone of Costa Rica.

2. The SOLUS methodology

2.1. Overall structure

SOLUS consists of three main components (Fig. 2): (1) a bioeconomic agricultural sector model of the linear programming (LP) type that incorporates the labor market as well as a multimarket structure for commodities, (2) two models of the expert-system type (called technical coefficient generators or TCGs) that define large numbers of production activities each of which is characterized by a specific technology, and (3) a geographic information system (GIS).

The LP model selects the optimal combination of production activities by maximizing the economic surplus generated by the agricultural sector in the region. TCGs are essentially expert systems that quantify input–output coefficients of a large number of production activities with their associated technologies (also referred to as land use systems) at the plot level (Hengsdijk et al., 1999). GIS is used to (i) spatially reference biophysical and economic data that characterize the region, (ii) manage these data to create input files for the TCGs and for the LP model, (iii) store and spatially reference LP model output, and (iv) create maps of both input and LP output data. Each of the three main components of SOLUS is discussed in greater detail below.

2.2. Linear programming model

The LP model for the NAZ of Costa Rica is a regional agricultural sector model that maximizes regional economic surplus subject to boundary conditions and goal constraints.[1] Constraints may be absolute, relating to resource endowments (e.g., availability of soil resources, labor availability) or normative (i.e., user-defined), linked to sustainability, environmental considerations, or the introduction of specific policy measures. In order to capture economic

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[1] The mathematical specification of the LP model can be found in Schipper et al. (2000). Its formulation in GAMS (Brooke et al., 1992) is included on a CD-ROM in Bouman et al. (2000).

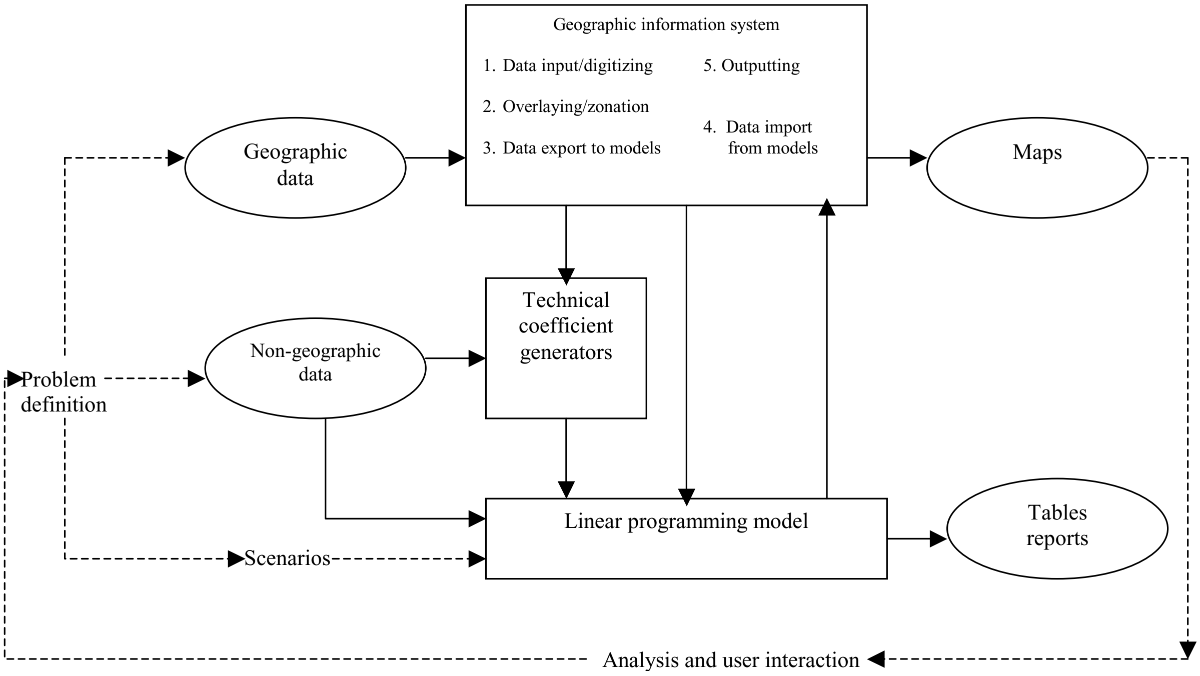

Fig. 2. Structure of SOLUS methodology with five steps in the use of GIS. Boxes are models and tools; ovals are data; blank names are activities; drawn lines are flows of data; dotted lines are flows of information.

surplus, the LP model is formulated with a multi-market structure for commodities. Depending on the type of commodity market, economic surplus consists either of the sum of the consumer and producer surpluses (domestic markets) or of the producer surplus alone (export markets). By maximizing the sum of these economic surpluses, demand and supply in all markets are equilibrated (Takayama and Judge, 1971). In domestic markets, supply from the NAZ competes with supply from other regions within Costa Rica, while in export markets it competes with supply from other countries. For a number of products (i.e., banana, palm heart, and plantain), the production of the NAZ constitutes a significant part of the national and/or world supply and prices of these products become endogenous. Following Hazell and Norton (1986), the regional demand functions were estimated (Geurts et al., 1997; Van der Valk, 1999) and linearized around an observed quantity and price. Regional own price elasticities of demand η_r were calculated as follows:

$$\eta_r = \eta\frac{1}{K} - \sigma_{nr}\frac{1-K}{K} \tag{1}$$

where η represents the national own price elasticity of demand, K is the share of the NAZ in total national production, and σ_{nr} is the supply elasticity from other domestic regions. Cross-price elasticities of demand were assumed to be zero. Estimates of own-price elasticities of supply were lacking and therefore set at 0.7, in line with Sadoulet and de Janvry (1995) and Mamingi (1997).

Product prices depend on location within the NAZ due to geographical variation in road density (Fig. 3), distance to markets (Fig. 4a), and road quality (Jansen and Stoorvogel, 1998). This geographical variation in product prices was addressed by dividing the NAZ into subregions, each with its own specific transport costs to the most relevant market (depending on the type of product and final destination). Transport costs were calculated on the basis of a regression model that relates unit transportation costs to geographical distance and road quality (Jansen and Stoorvogel, 1998). The subregions are the result of a GIS overlay of three zonation maps based on equal transport costs (maps can be found in Bouman et al., 1998b). The first map concerns the transport costs of agricultural products to the road

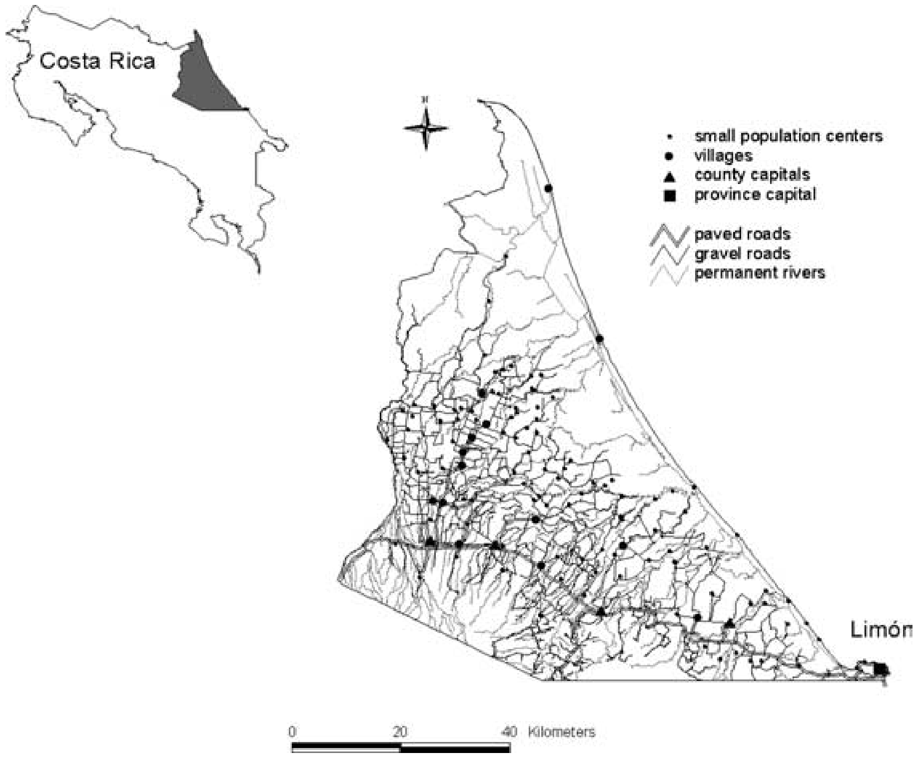

Fig. 3. Road infrastructure base map of the Northern Atlantic Zone.

in the Southwest of the NAZ, where the products leave the NAZ en route to the domestic market. The second map concerns livestock products shipped to the same destination. The third map concerns the transport of export products to the Limón sea harbor in the southeast of the NAZ. To keep the size of the model within limits, while still distinguishing meaningful transport zones, 12 "iso-transport cost" subregions were delineated (Fig. 4b).

In the LP model, farm-gate prices were calculated per subregion by subtracting transport costs from product prices in their respective market outlets in the NAZ. No significant spatial variation was found for prices of agricultural inputs (e.g., seed, fertilizer, and pesticides), so these were treated as exogenous and equal across subregions.

All production originating from the NAZ competes for limited land and labor resources. Land availability in each of the 12 subregions of the NAZ is specified for three soil groups (see next section), using map overlaying in GIS. Soil data were available from Wielemaker and Vogel (1993), Stoorvogel and Eppink (1995), and Nieuwenhuyse (1996). In order to let the agricultural sector in the NAZ compete for labor with other sectors and regions, potential labor availability in each subregion of the NAZ is divided into three components: the existing agricultural labor force in that subregion, the existing agricultural labor force in other subregions of the NAZ, and labor from outside the agricultural sector within the NAZ or from outside the NAZ. In each subregion, the first labor component is the cheapest, working at a fixed wage without transaction costs. Additional labor can be attracted from other subregions but involves additional transaction costs. The latter were approximated by transportation costs that were calculated on the basis of bus fares between the geographical centers of the subregions. Finally, labor in excess of the total regional labor pool can be attracted from elsewhere, but at higher wages according to an upward-sloping labor supply function. Similar to

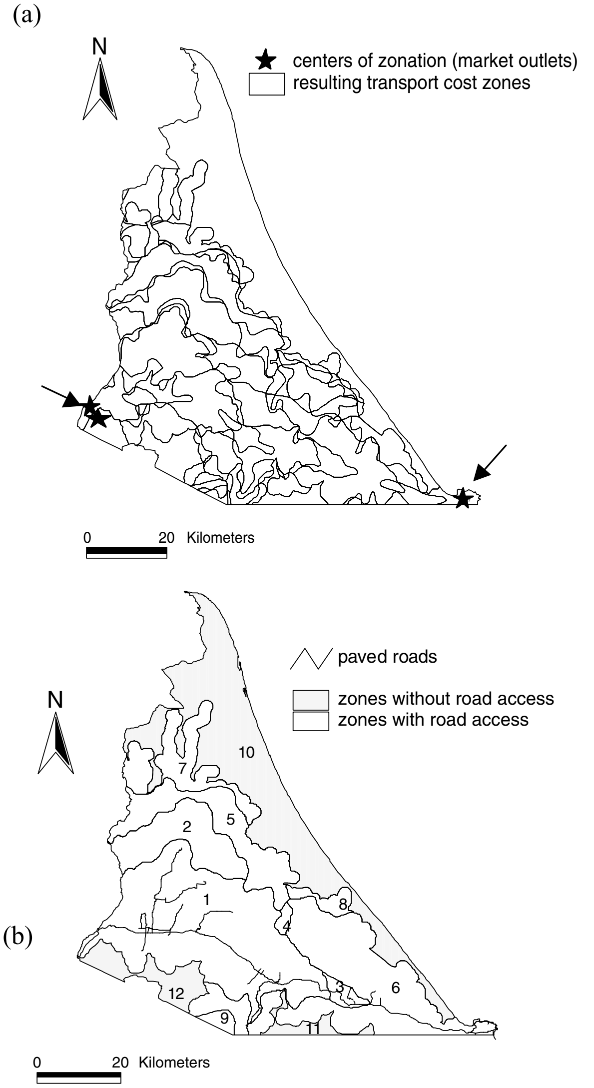

Fig. 4. (a) Overlay of three transport costs zones (upper) and (b) the resulting subzone map (lower). Subzones 10, 11, and 12 have no road access.

agricultural products, the regional labor supply elasticity, ε_r, for each sector/region r is given by

$$\varepsilon_r = \varepsilon\frac{1}{M} - \theta_{nr}\frac{1-M}{M} \qquad (2)$$

where ε is the national labor supply elasticity, θ_{nr} is the labor demand elasticity in the remainder of the economy, and M is the share of the labor in sector/region r in the national labor market. Values for the national labor supply elasticity and the labor demand elasticity in the remainder of the economy were set at, respectively, 0.2 and −0.5, in line with other studies (Bosworth et al., 1996). Using Eq. (2) and given a labor share of 0.05, the resulting ε_r of 13.5 for the labor supply elasticity in the NAZ agricultural sector implies a very gently upward-sloping labor supply function. Further details can be found in Schipper et al. (2000).

2.3. Technical coefficient generators

Land use activities include actual and alternative land use systems and are defined using two TCGs, one for crops and forests (Hengsdijk et al., 1998) and one for pasture-based cattle systems (Bouman et al., 1998a). Both TCGs were developed building upon concepts outlined by Stomph et al. (1994) and practical experience in related studies in the Netherlands (Habekotté, 1994), Europe (De Koning et al., 1995), and West Africa (Hengsdijk et al., 1996). Together, they cover the 13 major land use activities in the NAZ: eight crops (banana, black beans, cassava, maize, palm heart, pineapple, plantain, and natural forest for sustainable timber extraction) and five pasture types (three fertilized improved grass species, a grass-legume mixture, and a traditional mixture of natural grasses). These land use activities were combined with three major soil groups identified in the NAZ;[2] each subdivided into mechanizable and nonmechanizable subunits. Actual land use systems are quantified based on representative field survey data[3] (Hengsdijk et al., 1999).

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[2] See Section 4.1 for more details.

[3] These field survey data were mostly collected by a large number of M.Sc. level students who worked with staff of the Research Program on Sustainability in Agriculture (REPOSA), the joint research program between CATIE, Wageningen, and the Costa Rican Ministry of Agriculture that developed the SOLUS methodology, in the course of either thesis work or apprenticeships. The quality of the field data was guaranteed by close supervision of students by REPOSA staff. In general, the data regarding actual land use systems reflect crop husbandry practices of the most efficient farmers in the region. In addition, teams of experts were frequently consulted because of their knowledge about the livestock and cropping systems in the Atlantic Zone, which resulted in broadly discussed formulation methods of quantifying technical coefficients.

Alternative systems[4] were defined using the target-oriented approach (Van Ittersum and Rabbinge, 1997), with the restriction that soil nutrient balances must be kept in equilibrium (i.e., no changes in soil nutrient stocks for N, P, and K and therefore no soil nutrient mining). For alternative crop systems, different technology levels were defined by combining levels of mechanization, fertilizer use, and crop protection, the latter consisting of herbicide use versus manual weeding and various application levels of other pesticides. Weeding, fertilization levels, and stocking rate determine pasture technology, apart from the pasture type. A total of 1,352 crop systems and 1,756 pasture systems were defined. In addition, two herd types were distinguished (cattle breeding and cattle fattening), each of which was further subdivided into four animal growth rates. Finally, five types of feed supplements were also defined as possible substitutes for pasture-based feeding of cattle.

Technical coefficients were defined on a "per ha" basis and include yields, labor use, costs of inputs, and sustainability and environmental impact indicators. Technical coefficients are either averages per year (e.g. labor use) or annuities of the present value over the life span of the land use systems (e.g., yield, input costs). Based on the relevant sustainability issues in the NAZ, the following technical coefficients of sustainability and environmental impact were developed: soil nutrient balances for nitrogen (N), phosphorus (P), and potassium (K), where negative balances indicate soil mining; N losses to the environment via leaching (a possible water pollutant); (de) nitrification (as a proxy for emissions of the greenhouse gasses NO and N_2O); N volatilization (NH_3 being a potential contributor to acid rain); and the use of pesticides, expressed both as the total amount of active ingredients used and by an ordinal pesticide environmental impact index (PEII).[5] The latter takes into account not only the active ingredients used but also their degree of toxicity and persistence in the environment and is defined as follows:

$$\mathrm{PEII} = \frac{1}{Y} \sum_{\substack{\text{pesticides} \\ \text{applications}}} Q * f * \mathrm{TOX} * \sqrt{\mathrm{DUR}} \qquad (3)$$

where Y is the duration of the land use system in years; Q are the quantities of the pesticides used in kg; f is the fraction active ingredient in each pesticide; TOX is the toxicity of each active ingredient (based on World Health Organization [WHO] codes; see Jansen et al., 1995); and DUR is the persistence of the active ingredient in the environment in days. All land use systems defined by the TCGs describe specific quantitative combinations of physical inputs and outputs, and thus represent Leontief-type input–output technologies.

2.4. GIS

The analysis of land use scenarios with LP models has a long tradition and spans multiple scale levels including the farm enterprise (Sharifi, 1992), watershed (Barbier and Bergeron, 1999), district (Bassoco et al., 1973), region (De Wit et al., 1988; Veeneklaas et al., 1994), as well as the national (Bassoco and Norton, 1983) and international levels (Rabbinge et al., 1994). Similarly, GIS alone has also been used for land use analysis (e.g. Despotakis, 1991; Huising, 1993). Even though LP models are not spatial (Chuvieco, 1993) they can be linked to a GIS to relate the land use analysis to certain geographical features. However, since GIS does not provide tools for LP and no commercial LP software includes GIS facilities, examples of the true integration of LP and GIS (i.e., where

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[4] Technical coefficients of alternative production systems are mostly based on standard data regarding agronomic and animal husbandry relationships, empirical data and systems-analytical knowledge of the physical, chemical, physiological, and ecological processes involved. In situations where data were incomplete or lacking, or where processes are poorly understood, expert knowledge was used as a complementary information source. For some of the alternative land use systems, technical coefficients are based on the outcomes of farmer-managed experiments in farmers' fields. Examples include the technical coefficients of some of the silvipastoral and agroforestry-based systems for cattle, which were developed and tested over a number of years in close cooperation with farmers and as part of a Ph.D. thesis (see Ibrahim, 1994).

[5] Efforts aimed at determining the environmental impact of pesticide use started with the development of qualitative frameworks on the basis of soil survey data, using mostly expert knowledge to determine potential high-risk areas (see, e.g., Jury and Fluhler, 1992). The need for a more quantitative approach to the prediction of environmental impacts of pesticides originates in its economic implications (Bouma et al., 1993). An example is the approach used by Bessembinder (1997) who develops an index for pesticide leaching based on the likelihood of potential leaching for various chemicals and the amounts of active ingredients used. Our PEII is more comprehensive in that it also takes toxicity levels into account, but it does not differ between soil types.

both LP and GIS constitute integral parts of one and the same methodology) are very scarce. The SOLUS methodology is an exception in this respect, integrating GIS and LP for land use analysis at different scales (Bouman et al., 1999; Sáenz et al., 1999). In SOLUS, GIS is used to (i) spatially reference biophysical and economic data, (ii) manage these data to create input files for the TCGs and for the LP model, (iii) store and spatially reference LP model output, and (iv) create maps of both input and LP output data. Building on a concept introduced by Stoorvogel (1995), a framework of five steps was developed for the use of GIS in SOLUS (see also Fig. 2):

Step 1: Creation of base maps of relevant biophysical (e.g., climate, soil, topography), economic (e.g., population), infrastructure (e.g., roads), and administrative (e.g., regional boundaries) data. The thematic attributes that need to be stored in GIS are derived from the requirements of the TCGs and the LP model.

Step 2: In general, the region of interest needs to be stratified into homogeneous subregions or zones because of spatial variation in biophysical and/or economic characteristics. A zonation comprises two steps of map overlaying. First, maps of diagnostic attributes are overlaid to create the required homogeneous subregions. Next, the map with subzone boundaries is overlaid with other, nondiagnostic thematic maps to complete the attribute set of the new subzones. The distinction between diagnostic and nondiagnostic attributes is based on their importance in the description of production activities by the TCGs and in the objective function and set of constraints of the LP model. For example, in a topographically heterogeneous area, diagnostic attributes may be climatic and topographic features that affect agronomic and other biophysical relationships that are used in the TCGs. Nondiagnostic attributes that influence the structure of the LP model may include road infrastructure (affecting transport costs) and population density (influencing commodity demand and labor supply).

Step 3: Attribute data are exported to the TCGs and to the LP model. Climate and soil data are used in the calculation of input–output relations of production activities by the TCGs. Following common LP terminology, relevant attribute data are translated into so-called “right-hand side data” and “matrix coefficients” in the LP model. Examples of the former are available land and labor resources; examples of the latter are unit transport costs. All relevant attribute data are specified by subzone. A well-structured format facilitates data exchange between the GIS, the TCGs, and the LP model. In SOLUS, the semiautomated flow of data is based on space-delimited ASCII tables.

Step 4: Results of simulations with the LP model are returned to the GIS and stored as new attributes. They include both economic and other (environmental and sustainability) indicators for each subzone.

Step 5: Maps are generated for the various indicators, showing their absolute value and spatial distribution across the study region.

In scenario studies that explore the potential effects of alternative policy measures, steps 2–5 may have to be repeated more than once. The evaluation of previous scenario results (e.g., maps in step 5) may give rise to the formulation of new scenarios that may change the geographic resource base in step 2 and/or require recalculation of attribute data in step 3.

3. Case study region: the Northern Atlantic Zone of Costa Rica

3.1. Biophysical and socioeconomic conditions

The NAZ belongs to the humid tropical Caribbean lowlands and covers a total area of 447,000 ha with flat topography. Administratively, the NAZ coincides with the northern half of the province of Limón, between 10°00′–11°00′ latitude and 83°00′–84°00′ longitude (Fig. 1). Rainfall is high across all of the NAZ (3,500–5,500 mm per year) without a dry period (Gómez, 1986). Average daily temperature is 26°C. Soils are mostly andosols and inceptisols but vary highly in fertility and drainage conditions (Wielemaker and Vogel, 1993). Of the total area of 447,000 ha, 334,000 ha are suitable for agriculture. Of these 334,000 ha, 55,000 are protected for nature conservation (including 12,000 ha of national parks) or have a “semiprotected” status (indigenous reserves, forest reserves, wetlands). Some 28,000 ha consist of rivers, roads, urban area etc, leaving 251,000 ha available for agriculture. The area not available for agriculture (168,000 ha or some 38% of the total area) is mostly under natural forest cover. Current agricultural land use is dominated by pastures for beef cattle ranching (close to 200,000 ha) and banana plantations (some 35,000 ha). Secondary crops (total about 13,000 ha) include plantain, palm heart, root and tuber crops, maize, papaya, pineapple, and ornamental plants. Tropical rain forest once covered the entire area, but is now to a large extent restricted to wetlands, inaccessible mountain areas, and (semi-) protected areas. Negative environmental effects of deforestation include land degradation and waste losses (pesticides, nutrients, greenhouse gasses) to the environment from agricultural activities (Keller et al., 1993; Veldkamp et al., 1992). In cattle ranching, soil mining and the resulting pasture degradation have become problematic, reducing cattle productivity and farmers' income (Bouman and Nieuwenhuyse, 1999). Colonization of the NAZ started at the end of the last century but accelerated in the past 30 years (Nieuwenhuyse et al., 2000). Rapid structural transformations were and are taking place in the ecological, agricultural, and socioeconomic conditions of the region, in part responding to various structural adjustment programs that were introduced since 1987 (Jiménez, 1998).

3.2. Agricultural policy issues

Questions and problems surrounding the policy debate related to agricultural sector development in the NAZ vary not only according to the changing biophysical and socioeconomic conditions in the region, but also depend on the type of stakeholders involved. Typically, the development goals and type of issues that are of primary concern to different stakeholders are intimately related to the latter's time frame: farmers and plantation owners are mostly concerned with short-term issues that immediately affect their income; policy makers tend to focus on medium-term questions that relate to the performance of the agricultural sector as a whole; and long-term sustainability-related issues mostly draw the attention of environmental protection and nature conservation agencies. Even though, until recently, the NAZ was not a prime focus of attention for policy makers in the capital city of San José, political interest in the area has grown as a result of the increasingly conflicting policy objectives concerning the short-term profitability of agricultural production and its longer-term sustainability. In addition, environmental quality, including combating deforestation and the establishment and maintenance of nature reserves, now looms high on the policy agenda. In general, since the early 1990s, the policy debate has centered around the following priority issues:[6]

Sustainability of current farm practices: Conversion of forests to agricultural land (especially pastures) has led to considerable soil nutrient mining and consequent land degradation (Jansen et al., 1997), pointing toward the unsustainability of the technologies embedded in most actual land use systems (Table 1). Since at the regional level pasture is the major land use, soil mining in beef cattle ranching is an important contributor to overall nutrient depletion. Beef cattle are mainly held on natural unfertilized pastures with high stocking rates. Combined with high rainfall, highly permeable soils, and high N turnover rates (Bouman and Nieuwenhuyse, 1999), this results in an N depletion of 60–70 kg ha^{-1} yr^{-1}. This implies that soil nutrients become exhausted over time, leading to declining pasture yields and decreasing live weight gains (see Bulte et al., 2000a for similar results in an optimal control framework). The use of pesticides is particularly high in banana plantations and cassava production.

Environmental protection: The sequence of structural adjustment programs implemented since the late 1980s has emphasized production of both traditional and nontraditional export crops and stimulated higher usage of chemical inputs (particularly pesticides), which in turn has led to increased environmental and human health damage (Jansen et al., 1998; Wesseling, 1997).

Conservation of forest resources: On the one hand, the increasing awareness of the multifunctional character and associated values of forest lands has led to the development of a number of innovative schemes and policies aimed at capturing some of these values (Bulte et al., 2000b; Jansen et al., 2001); on the other hand, the protected status of some national

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[6] In order to better define relevant scenario runs with the SOLUS methodology, a study was undertaken to identify the development views, objectives, and goals of various institutions, stakeholders, and policy makers in the NAZ in relation to land use policies (see Wilhelmus, 1998).

Table 1
Current technology scenario and technological progress scenario

	Current technologies (actual land use systems only)	Technological progress (all available technologies)
Economic indicators		
Economic surplus (US$$10^6$)	221	292
Employment (days 10^3)	9,039	8,661
Land use (% of total land area suitable for agriculture [251,000 ha])		
Pastures	69	76
–Natural	69	60
–Grass-legume	0	16
–Fertilized pastures	0	0
Forest (including unused land)	0	0
Crops	31	24
Sustainability indicators (depletion of soil nutrients [kg/ha/yr])		
N	51	62
P	3	−0.5
K	113	21
Environmental indicators		
Nitrogen lost by (de) nitrification (kg/ha/yr)	15	41
Nitrogen lost by leaching (kg/ha/yr)	90	94
Nitrogen lost by volatilization (kg/ha/yr)	15	24
Total nitrogen lost to the environment (kg/ha/yr)	120	159
Pesticide active ingredients used (kg/ha/yr)	12	8
Pesticide Environmental Impact Index	398	264

parks that conserve unique tropical forest habitats is occasionally disputed and/or violated by farmers and wood loggers.

Technological change: Since the late 1990s, national agricultural policy in Costa Rica has placed renewed emphasis on food security without compromising export-led agricultural growth: efficient production of domestically consumed food crops and livestock products is promoted through renewed attention for technological progress aimed at increasing the competitiveness of small- and medium-scale farms (SEPSA, 1997).

Improving marketing opportunities: The urgent need for measures aimed at strengthening the ability of small- and medium-scale farmers to market their produce, including the extension and upgrading of the currently highly variable road network, is increasingly recognized (Jansen and Van Tilburg, 1996; Roebeling et al., 2000).

In the next section, the SOLUS methodology is used to address some of these issues. Its capability to quantify information about economic and sustainability trade-offs in a way that is helpful to decision makers is illustrated through a number of scenarios, where a scenario is defined as the maximization of the objective function under a coherent set of constraints.

4. Application of SOLUS

4.1. Implementing GIS

The five steps involved in the use of GIS were implemented as follows:

Step 1: Base maps were created for soil type, climate characteristics, topography, road infrastructure, protected areas, and administrative boundaries. The 74 soil types identified in the original soil survey by Wielemaker and Vogel (1993) span 21 soil series, which were aggregated into four major soil groups, based on fertility and drainage criteria: fertile well-drained soils, infertile well-drained soils, fertile poorly drained soils, and soils unsuited for agriculture (Nieuwenhuyse et al., 2000; Fig. 5). Natural parks with a protected status and unsuitable soils were excluded from the soil resources

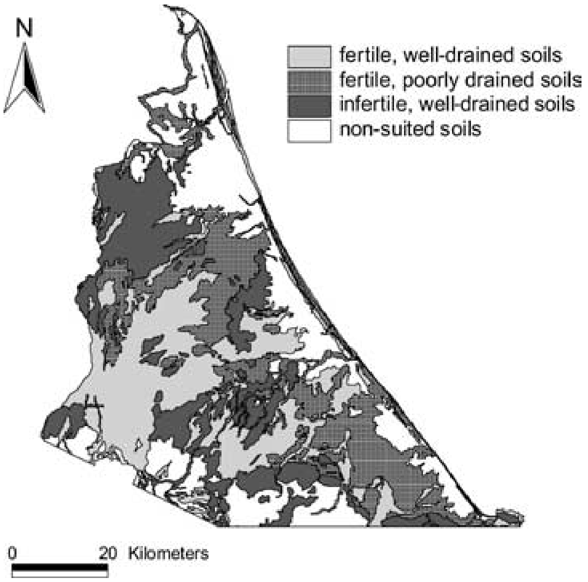


Fig. 5. Soil base map of the Northern Atlantic Zone.

available for agriculture. Agricultural labor availability was derived for each administrative unit by using data from the 1984 population census and zone-specific population growth rates (DGEC, 1987, 1997a; 1997b; Schipper et al., 2000). Road infrastructure and rivers were digitized from 1:25,000 topographic maps and checked by ground surveys. Examples of base maps include the road infrastructure map (line map; Fig. 3); and the soil map (polygon map; Fig. 5).

Step 2: The NAZ is quite homogeneous in climate and topography, to such an extent that the minor geographical differences in climate and topography have no significant effect on its suitability for most land use systems. In addition, soil types are distributed rather evenly throughout the area, so there was no need for zonation based on biophysical characteristics, and land use systems in the TCGs were defined with spatial reference to the three soil groups only. However, as discussed in Section 2.2, road infrastructure varies considerably, ranging from a relatively dense network in the South to a relatively sparse one in the North (Fig. 3). Since road infrastructure affects product transportation and labor mobility costs (both of which are major determinants of the economics of production), road infrastructure was used in the zonation of the NAZ. For each subzone, soil and labor endowments were calculated by overlaying the subzone map with the soil and labor availability base maps.

Step 3: Relevant characteristics of the three soil groups were exported to the TCGs for calculation of inputs and outputs such as fertilizer requirements and nutrient losses. For each subzone, data exported to the LP model included soil and labor resources (right-hand side data), unit transport cost for products, and labor mobility costs across subzones ("matrix coefficients").

Step 4. Results of optimizations of the LP model were returned to the GIS in the form of variables of interest, summed over all selected land use systems per subzone.

Step 5: In order to highlight and visualize trade-offs between conflicting objectives, maps were generated that depict land use and other variables of interest (e.g., Figs. 7 and 8 and in Section 5.4).

4.2. Model validation and scenario definition

In order to validate the agricultural sector model in SOLUS, a current technology scenario was run in which only actual land use systems were offered to the LP model, without any sustainability or environmental constraints. The current technology scenario mimics the actual land use pattern in the NAZ in 1996 in broad terms and is dominated by forest, pasture, and bananas (Fig. 6).

The next session discusses the following types of alternative scenarios:

1. Technological change in agricultural production,
2. Conservation of forest resources,
3. Decreasing pesticide use, and
4. Increasing sustainability and environmental protection.

5. Results and discussion

5.1. Technological progress in agricultural production

The effects of technological progress were assessed by offering the entire spectrum of known land use technologies (as defined by the TCGs) to the LP model

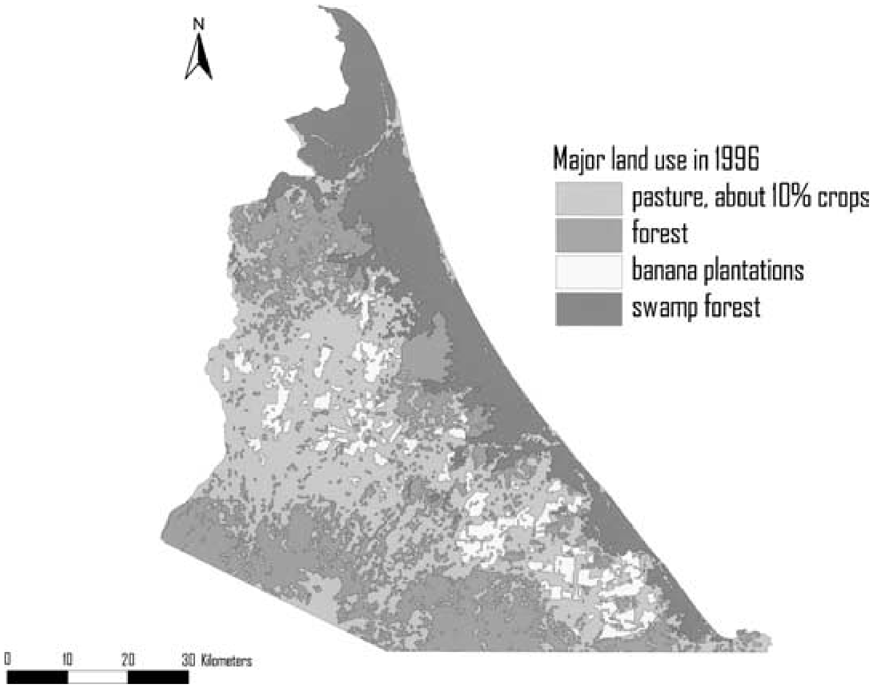


Fig. 6. Actual land use in 1996 based on satellite images, aerial pohotographs, and field survey data.

(as opposed to only actual technologies in the current technology scenario). Technological progress, essentially producing more with the same or lesser resources (land, labor), has important effects on economic surplus, employment, sustainability, and environmental indicators (Table 1). Relative to the current technology scenario, economic surplus and labor productivity increase by 33% and 38%, respectively. As a consequence, employment decreases slightly. The results illustrate a number of trade-offs among the sustainability and environmental indicators. Compared to the current technology scenario, soil K mining and pesticide use decrease to a significant extent but soil N mining and N loss to the environment show slight increases. Nevertheless, it seems safe to conclude that most people would probably prefer the technological progress scenario over the current technology scenario, given the latter's substantial economic advantages and mixed environmental implications. Improved technologies as incorporated in the TCGs are based on sound agronomic possibilities, not only theoretically but also as observed by current practices on the best farms (Hengsdijk et al., 1999). The fact that most of these technologies have thus far been adopted only sparsely has to do with access to financial resources, technical knowledge, and marketing opportunities, all of which are insufficient among small- and medium-scale farmers in the NAZ of Costa Rica (Jansen and Van Tilburg, 1996; Jansen et al., 1997).

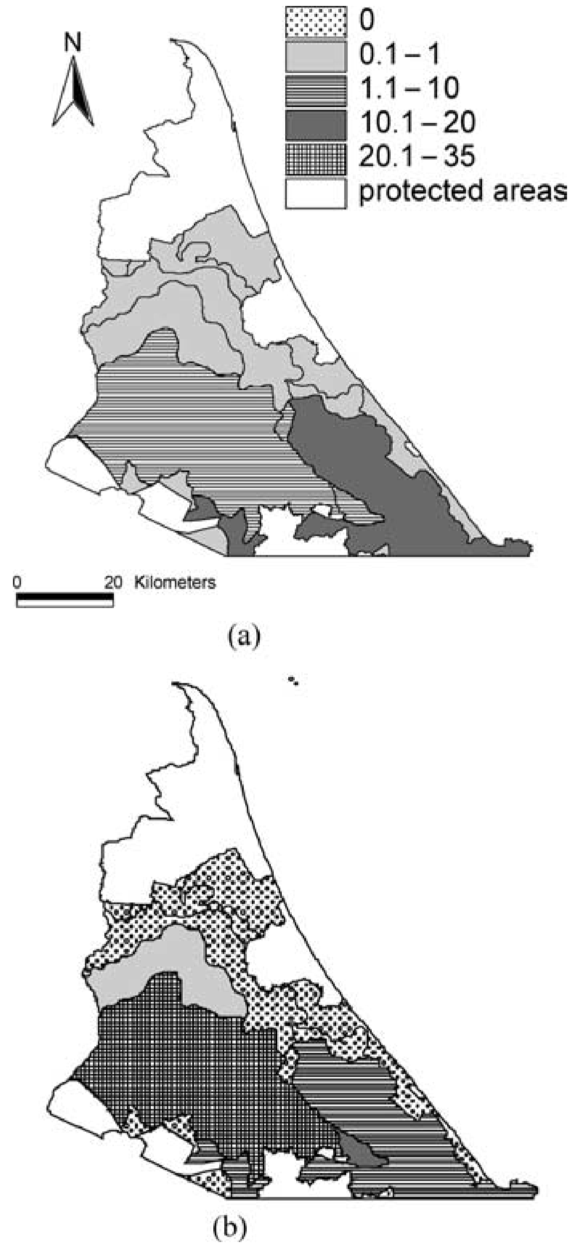
5.2. Forest conservation

The forest conservation scenario analyzes the effect of a "payment for environmental services (PES)" policy, modeled through the allocation of premiums to the land use type "natural forest." The currently operational PES scheme, initiated after the international discussion about global warming at the 1992 Rio Conference on Sustainable Development, allows for a payment of US\$40 ha^{-1} yr^{-1} to owners of natural forest lands in return for their protection. Even though this payment (financed through a tax on gasoline) is about double the amount that can be earned through sustainable wood extraction (Bulte et al., 2000b), it is still well below the average opportunity costs of forest land, which are estimated at around US\$120 ha^{-1} yr^{-1} and largely determined by the returns to beef cattle raising

(a)

(b)

Fig. 7. Percentage of suitable land area under crops (%) in (a) the technological progress scenario and (b) the sustainability and environmental scenario no. 6.



(a)

(b)

Fig. 8. Pesticide use (active ingredients in kg/ha) in (a) the technological progress scenario and (b) the sustainability and environmental scenario no. 6.

on natural pasture (Jansen et al., 1997). Indeed, model simulations show that a payment of US\$110 ha^{-1} yr^{-1} is still not sufficient to induce landowners to maintain their natural forests. On the other hand, a payment of US\$120 ha^{-1} yr^{-1} would lead to an increase in forest area of about 35,000 ha and a payment of US\$130 ha^{-1} yr^{-1} would result in an additional 115,000 ha of natural forest, mainly by converting pastures back to forest. It can be concluded that the current payment level has been largely effective in protecting forest stands on land that has low opportunity costs (mostly land that is unsuitable for agricultural use). However, even though Costa Rican law does not allow conversion of natural forests to agricultural land, the current payment level provides insufficient incentives for conservation of forest on lands with higher agricultural potential.

5.3. Decreasing pesticide use

In Costa Rica, regulation and control of agricultural input use, particularly of pesticides, has been identified as an important policy option in a campaign to reduce negative environmental externalities of agricultural production (SEPSA, 1997). Compared with many other countries, the use of pesticides in Costa Rica is high at about 4 kg active ingredients (a.i.) per capita per year, or 6 kg yr^{-1} per hectare of arable land (Von Düszeln, 1990). Policies aimed at reducing pesticide use have traditionally consisted of legislative measures and the potential of economic instruments has generally been overlooked. An example of an economic instrument is pesticide taxation, and a distinction can be made between a flat tax and a progressive tax. The latter's magnitude is linked to the environmental damage caused by a specific pesticide as measured by the PEII (Eq. [3]). Table 2 shows that taxing all pesticides at a uniform rate of 100% leads to a reduction in environmental damage of only 4% and that such a flat tax instrument is very expensive (economic surplus is reduced by nearly one-fifth). In contrast, a progressive tax regime, where different tax rates are applied to three categories of pesticides depending on their degree of toxicity, would lead to a much larger reduction in damage to the environment and at comparatively low costs.

Table 3
Restrictions in the six sustainability-environmental protection scenarios

Scenario	Restrictions
1	N loss to environment, quantities of pesticides used and pesticide index ≤80% of their values in the technological progress scenario
2	N loss to environment, quantities of pesticides used and pesticide index ≤50% of their values in the technological progress scenario
3	No soil N mining (zero soil N balances)
4	No soil N, P, and K mining (zero soil N, P, and K balances)
5	Combination of scenario 4 with scenario 1
6	Combination of scenario 4 with scenario 2

5.4. Increasing sustainability and environmental protection

In order to simulate options for achieving different degrees of sustainability and environmental stewardship in agricultural production in the NAZ, six different sustainability-environmental protection scenarios were analyzed (Table 3). Since the latter all involve the use of improved technological options, they were evaluated relative to the technological progress scenario (see Section 5.1).

The overall results of these scenarios show that there is considerable scope to use land in a more sustainable and environment-friendly way. However, the cost (in terms of a reduction in economic surplus) of sustainability and/or environmental improvement depends largely on the type and degree of improvement pursued. Scenario 1 demonstrates that a 20% decrease in N losses to the environment and in environmental damage from pesticide use can be achieved for a

Table 2
Economic and environmental effects of alternative ways of taxing pesticide use

Type of pesticide	Flat tax	Progressive tax regimes		
		Regime A	Regime B	Regime C
Slightly toxic (%)	100	20	20	10
Medium toxic (%)	100	50	50	30
Very toxic (%)	100	200	100	150
Indicators (% change relative to current technology scenario)				
Economic surplus	−19	−4	−4	−2
Environmental damage (PEII)	−4	−82	−2	−82

Table 4
Results of six sustainability-environmental protection scenarios

Sustainability-environmental protection scenario[a]	1	2	3	4	5	6
Economic indicators						
Economic surplus[b]	−5	−28	−10	−17	−20	−35
Employment[b]	−21	−46	3	−4	−21	−47
Land use[c]						
Forest (%)	10	52	40	56	79	93
Pasture (%)	78	41	46	34	12	4
Crops (%)	12	7	14	10	9	3
Sustainability indicators						
Soil nitrogen balance (kg/ha/yr)	−50	−29	0	0	0	0
Soil phosphorus balance (kg/ha/yr)	1	0	0	0	0	0
Soil potassium balance (kg/ha/yr)	−14	−10	−33	0	0	0
Environmental indicators						
Nitrogen lost by (de)nitrification (kg/ha/yr)	31	20	40	37	31	20
Nitrogen lost by leaching (kg/ha/yr)	75	47	118	92	65	44
Nitrogen lost by volatilization (kg/ha/yr)	20	12	22	23	17	12
Total nitrogen lost to the environment (kg/ha/yr)	126	79	180	152	113	76
Pesticide active ingredients used (kg/ha/yr)	6	4	7	7	6	4
Pesticide Environmental Impact Index	211	132	96	98	40	25

[a] See Table 4 for scenario definitions.
[b] Economic surplus and employment in percentage changes from the technological progress scenario (see Table 1).
[c] Land use in the percentage of the usable total of 251,000 ha.

relatively modest decline in economic surplus of 5%. However, scenario 2 shows that the marginal costs of a further improvement in this type of environmental protection increase rapidly: a 50% improvement decreases economic surplus by 28%. A progressive tax on pesticides is likely to be much more cost-effective (see Section 5.3) and easier to implement as well. Preserving only the soil N stock (scenario 3) comes at a cost of a 10% decrease in economic surplus, while maintaining soil N, P, and K resources makes the economic surplus decline by 17% (scenario 4). Achieving sustainable use of soil resources while protecting the environment at the same time as in scenarios 5 and 6 is expensive, costing up to over one-third of economic surplus. The improvements in sustainability and environmental protection are mainly accomplished by a decrease in pasture area and by shifting technologies in the selected land use systems (e.g., increased use of fertilizer, substitution of herbicide use for manual weeding).

Besides trade-offs between economic indicators on the one hand and indicators of sustainability and environment on the other, there also exist trade-offs between individual sustainability and environmental indicators, in addition to spatial trade-offs. Trade-offs between biophysical indicators are illustrated by comparing the results of scenario 3 to those of the technological progress scenario: whereas scenario 3 exhibits a zero soil N balance, soil K mining, and the amount of N lost by leaching actually worsen. Spatial trade-offs for a particular indicator are conveniently illustrated in maps created with a GIS. As an example, we present results for land used for crops (Fig. 7) and pesticide use (Fig. 8) in the technological progress scenario (a) and in scenario 6 (b). In the technological progress scenario, the percentage of land used for cropping is highest in the southern zones and lowest in the northern zones, mainly because of increasing transport costs from south to north (Fig. 7a). In scenario 6, much less land is used for cropping than in the technological progress scenario (Fig. 7b). Note that in subzones 9 and 12 located in the south of the NAZ (see Fig. 4b), the percentage area under crops is substantial in the technological progress scenario but zero in scenario 6, again because of high transport costs due to relatively poor road infrastructure (see Fig. 3). Fig. 8a depicts the amount of active pesticide ingredients used per hectare in the technological progress scenario, averaged over all land used for agriculture in each subzone. Differences among subzones relate to crop types and technologies (data not shown). Compared to the technological progress scenario, scenario 6 results in a decrease in the average amount of pesticides applied per unit area in most subzones (Fig. 8b). However, in zones 1 and 3, the use of pesticides actually increases, mainly as a result of changes in crop production technologies.

Figs. 7 and 8 and illustrate the geographical dimension of potential conflicts and trade-offs that exist between farmers' short-to-medium-term profit maximization goal and environmentalists' more long-term focus on minimizing environmental pollution caused by the use of pesticides (Jansen et al., 2001). Moreover, maps of this kind provide relatively uncomplicated insight into the location of "hotspots" where local objectives (at the level of the subzone) may conflict with objectives at a higher level (in this case, the entire NAZ).

Finally, for the scenario analyses presented in this article it was not necessary to change the geo-referenced calculation units of SOLUS, i.e., steps 2–5 mentioned in sections 2.4 and 4.1 (and illustrated in Fig. 2) needed to be executed only once. However, other scenario types would demand re-definition of land units and steps 2–5 would need to be carried out with new data layers. For example, the geographical distribution of the road infrastructure in the NAZ is currently highly unequal. The SOLUS methodology is ideally suited to explore the economic, environmental, and sustainability consequences of changes in land use after improvement of accessibility. A scenario consisting of new road construction and/or improving existing roads would require a new zonation of the NAZ in step 2, and consequently lead to new map overlaying and calculation of attribute data such as resource data and transport costs.

6. Conclusions

This article has presented an interdisciplinary methodology called SOLUS for regional land use analysis that enables quantification of trade-offs between economic, environmental, and sustainability objectives. Special attention is given to the role of GIS, which is shown to be crucial for data manipulation, for providing geo-referenced input data for the other components of SOLUS, and for spatially displaying model output results. SOLUS is applied to a case study of the Northern Atlantic Zone (NAZ) of Costa Rica, where the current land use pattern is shown to be highly unsustainable and harmful to the environment as well. However, the tools and models employed in SOLUS are sufficiently generic to allow its implementation to other regions with different biophysical and economic conditions (see e.g., Sáenz et al., 1999).

The use of SOLUS in the NAZ is illustrated through a number of scenarios aimed at environmental protection and increasing biophysical sustainability, while maintaining the economic surplus to the best extent possible. The specific results obtained with these scenarios have a number of important implications for policy makers and other stakeholders concerned with agricultural development in the NAZ, including cattle farmers, small crop producers, plantation owners, and environmentalists. First, the technological progress scenario suggests that improved agricultural production technologies have large potential for improving both welfare and several aspects of sustainability in the NAZ of Costa Rica. Since such technologies are known but not (yet) adopted on a wide scale, investments aimed at improving the extension services and increased access to credit may have high potential returns. In this context it is worth mentioning that the Interamerican Development Bank (IADB) approved a loan in 2002 that will enable the Costa Rican Ministry of Agriculture and Livestock (MAG) to do just that. Second, if policy makers want to increase the efficiency of the system of payment for environmental services in order to maintain the remaining natural forests in the country, the current scheme may need to be revised based on the opportunity costs. Third, the negative environmental effects of pesticides are best mitigated through a progressive tax on their use. Such a progressive tax is substantially more efficient than either a flat tax or a policy of quantitative limitations on pesticide use. The latter is particularly expensive when combined with the sustainability objective of zero soil nutrient balances, resulting in a loss of about one-third of the economic surplus in the region. Fourth, under currently known technologies, maintaining the soil's N, P, and K resources can be achieved at a cost of 17% of the regional economic surplus. Finally, negative environmental externalities caused by N waste losses and pesticide use are, in economic terms, best mitigated by reducing the cultivated area.

However, in such situations environmental pollution may be concentrated in relatively small areas, resulting in spatial trade-offs where local goals may conflict with regional goals.

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