AN INTEGRATED METHODOLOGY FOR SUSTAINABLE LAND USE EXPLORATION USING GIS*

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ABSTRACT

A methodology called SOLUS (Sustainable Options for Land Use) was developed to quantify trade-offs between socio-economic and sustainability objectives in explorative land use studies on regional scale. SOLUS integrates various tools and techniques of which Linear Programming, Technical Coefficient Generators and Geographic Information Systems are the most important. A five-step procedure was developed to use GIS to spatially reference bio-physical and socio-economic parameters, to create from these data input for the TCGs and the LP model, to store and spatially reference LP model output data, and to create maps of both model input and output data. Maps are ideally suited to visualize trade-offs on a regional scale, and to indicate 'hot-spots' where local interests may conflict with regional interests. The methodology is illustrated for the Northern Atlantic Zone of Costa Rica.

1 INTRODUCTION

Issues surrounding the debate about the development of the agricultural sector generally center around the question of how to achieve a certain level of food security while simultaneously providing sufficient income for food producers. More recently, the concern for environmental issues has entered the debate. Land use has obvious implications for farm income and the various dimensions of sustainability such as soil mining, nutrient losses and pesticide use. There is a need for tools and models that are capable of quantifying trade-offs that occur between socio-economic and sustainability-related objectives. This paper presents a methodology for the exploration of sustainable land use options at the regional level by quantifying such trade-offs. The methodology is called SOLUS (Sustainable Options for Land Use; Bouman et al., 1998) and was developed by the Research Program on Sustainability in Agriculture (REPOSA) in Costa Rica. SOLUS evolved from a previous methodology that operated at the level of the settlement (Stoorvogel et al., 1995). A main challenge in the development of SOLUS consisted of the integration of bio-physical with socio-economic information and models on a geo-referenced basis. A concept was developed to use GIS as a means to

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archive and manipulate geo-referenced data, to link GIS data to models of land use exploration, and to spatialy present model results. In this paper, SOLUS and the role of GIS are illustrated with a case study for the Northern Atlantic Zone (NAZ) of Costa Rica.

2 METHODOLOGY

2.1 SOLUS

The core of SOLUS consists of *i*) a linear programming (LP) model, *ii*) models to quantify land use activities in terms of inputs and outputs, called Technical Coefficient Generators (TCGs), and *iii*) a Geographic Information System (GIS), (Figure 1). The LP model selects for an entire region cropping and livestock land use options from a number of alternatives while maximizing regional economic surplus subject to boundary conditions and goal restrictions. The latter are related to the available amount of resources, marketable volumes of products, and sustainability and environmental considerations. The maximization of the objective function under a set of coherent restrictions is called a scenario. Trade-offs between economic and sustainability objectives are quantified by running the LP model for different scenarios. Land use options to feed the LP model are generated by the TCGs, and are quantified in terms of so-called technical coefficients. Technical coefficients are inputs and outputs of land use options and include such things as yield, costs, labour use, and sustainability indicators. Sustainability indicators currently operationalized are the soil nutrient balance (a negative balance indicates soil mining), nitrogen losses to the environment, and the use of pesticides expressed as amount of active ingredients applied and a so-called Pesticide Environmental Index that takes into account toxicity and persistence in the environment as well.

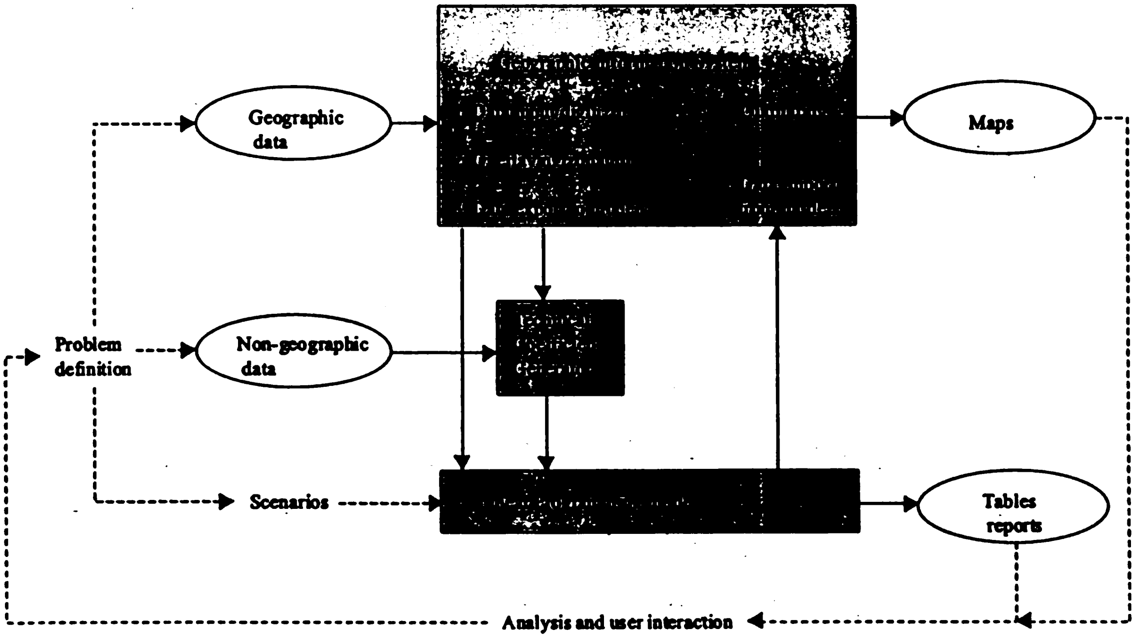


Figure 1. Structure of SOLUS. Gray boxes are models and tools; blank ovals are data; blank names are activities; drawn lines are flow of data; dotted lines are flow of information.

Crop and pasture land use options are defined as combinations of a land unit with a crop/pasture type cultivated with a specific technology. For the livestock sector, non-land based animal production systems (herds) and supplementary feed acquisition systems are defined as well. The TCGs generate production systems based on the 'target oriented' approach (Van Ittersum & Rabbinge, 1997): a number of target production levels and production technologies are predefined by the user and subsequently the amount of required inputs (e.g., fertilizers, crop protection agents, labour) are quantified by the TCGs. This way, a large number of alternatives can be generated that vary in socio-economic (costs, labour use) and sustainability technical coefficients.

2.2 THE ROLE OF GIS

GIS is used to *i*) spatially reference bio-physical and socio-economic geographic features, *ii*) to manipulate these data to create input files for the TCGs and for the LP model, *iii*) to store and spatially reference LP model output, and *iv*) to 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 (Figure 1):

Step 1: Creation of base maps of relevant bio-physical (e.g. climate, soil, topography), socio-economic (e.g. population distribution), infrastructure (roads) and administrative (e.g. districts, cantons) data. The thematic attributes that need to be stored in GIS are derived from the requirements of the models used in SOLUS, namely the TCGs and the LP model.

Step 2: In general, a regional area needs to be stratified into homogeneous sub-zones because of spatial variation in bio-physical or socio-economic land characteristics. A zonation comprises two steps of map overlaying. First, maps of diagnostic attributes are overlaid to create the required homogeneous sub-zones. Next, the map with the sub-zone boundaries is overlaid with the other non-diagnostic thematic maps to complete the attribute set of the new sub-zones. The distinction between 'diagnostic' and 'non-diagnostic' attributes is based on their importance in the calculation of land use options by the TCGs and in the objective function and constraints in the LP model. For instance, in a topographically heterogeneous area, diagnostic attributes may be climatic and topographic features that affect the production input-output relations as used in the TCGs. Non-diagnostic attributes might then be road infrastructure and population density.

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 land use options by the TCGs. In the LP model, relevant attribute data are translated into so-called Right Hand Side data and Matrix Coefficients (LP terminology). Examples of the first are available land and labour resources; examples of the second are transport cost prices. All relevant attribute data should be specified per sub-zone. A well-structured format facilitates data exchange between GIS and the models. In SOLUS, a semi-automated flow of data between GIS and the LP model is based on simple space-delimited ASCII tables.

Step 4. Results of optimizations with the LP model are returned to the GIS. The imported LP output variables are the socio-economic and sustainability trade-off values for each sub-zone separately, and are stored as new attributes in the GIS.

Step 5: Maps are made of various trade-off variables, showing their absolute value and spatial distribution in the area under study

In scenario-based studies of land use exploration, steps 2-5 may typically have to be repeated more than once. The evaluation of previous scenario results (e.g. maps of step 5) may give rise to the formulation of new scenarios that may change the geographic resource base or require re-calculation of attribute data in step 3 (Figure 1).

3 CASE STUDY: THE NORTH ATLANTIC ZONE OF COSTA RICA

3.1 SITE DESCRIPTION

The North Atlantic Zone (NAZ) is in the Caribbean lowland of Costa Rica, and our specific study area covers the northern half of the province of Limón, roughly between 10°00' and 11°00' latitude and 83°00' and 84°00' longitude. The humid tropical climate is characterized by a mean daily temperature of 26 °C, a mean annual rainfall of 3500-5500 mm, and average relative humidity of 85-90%. The area is mainly flat and elevation varies from 0 to 400 m a.s.l. The total surface is about 447,000 ha, 334,000 ha of which is suitable for agriculture. From this 334,000 ha, some 55,000 ha is protected area for nature conservation. Current land use is natural forests (49%), cattle ranching (38%), banana plantations (10%) and crops (3%). Substantial deforestation has taken place since the late nineteenth century. Negative environmental effects of deforestation include land degradation and nutrient losses to the environment from agricultural activities. In cattle ranching, soil mining and resulting pasture degradation have become a serious problem, reducing production and farmers' income. Reforms in agricultural policy since 1987 have affected production structures for cropping activities and have put pressure on crop-farmers' income. A recent concern in the NAZ is raised by environmentalists on environmental and human effects of relatively large amounts of pesticides used and nutrient losses to the environment, especially in the cultivation of bananas. The protected status of some national parks, that conserve unique tropical forest habitats, is sometimes disputed/violated by farmers and wood loggers. Finally, Costa Rica is faced with an increasing unemployment rate, so that employment in agriculture is of general concern to the government.

Given the issues mentioned above, there are various 'stakeholders' in the NAZ that may be characterized by specific development goals: cattle farmers, small crop producers, banana companies, wood loggers, environmentalists and the local/national government. Derived trade-offs that need to be quantified in land use exploration concern socio-economic (production, income, employment) and sustainability (soil mining, nutrient losses, pesticide use) parameters.

3.2 APPLICATION OF SOLUS

The TCGs were used to generate 1532 cropping activities, 1756 pasture activities, eight herd types and five feed supplements. The LP model selected, per sub-zone on each soil type the optimal combination of cropping and livestock activities by maximizing total NAZ economic surplus. Fixed boundary conditions included land and labour resources, product and livestock balances, and market constraints for products and labour. Optional restrictions concerned sustainability issues, e.g. maximum allowable soil nutrient balance, nitrogen losses and pesticide use. To illustrate SOLUS' capabilities to quantify socio-economic and sustainability trade-offs, a 'base' scenario was run without any sustainability constraint on land use, and a number of 'sustainability' scenarios where restrictions on sustainability parameters were gradually imposed from light (e.g. only a 20% reduction in regional pesticide use) to severe (e.g. zero soil nutrient balance combined with 50% reduction in pesticide use and nutrient losses).

The five steps involving the GIS were implemented as follows:

Step 1: Base maps were created for soil type, climate characteristics, topography, road infrastructure, protected areas, and administrative boundaries. Twenty-one originally defined soil series were grouped into three major categories based on the most important characteristics with respect to agricultural land use. Natural parks with a protected status were excluded form the land resources available for agricultural activities. Agricultural labour availability was derived for each administrative unit by using population census data and zone-specific population growth rates. Figure 2 gives the soil and road infrastructure base maps.

Step 2: The whole NAZ is homogeneous in climate and topography, and soil types are distributed rather evenly throughout the area. Therefore, there was no need for zonation based on bio-physical characteristics, and land use options were generated with spatial reference to the three soil types only. However, road infrastructure varies considerably, ranging from a relatively dense network in the southern part to a relatively sparse one in the northern part. Since road infrastructure affects product transportation and labour mobility costs, which are major determinant in the economics of production, this feature was used in zonation of the NAZ. Based on road quality and geographical distances between farm gates and market outlets, transportation cost models were developed for different classes of products. Figure 3a gives the overlay of three maps of transport cost zones derived from the application of these transport costs models for three product types (export crops, domestic crops, meat) with their respective market outlets. 'Cleaning' of this overlay resulted in 12 sub-zones (Figure 3b). For each sub-zone, soil and labour endowments were calculated by map overlaying. Labour mobility costs between sub-zones were calculated on the basis of bus fares between centers of each sub-zone.

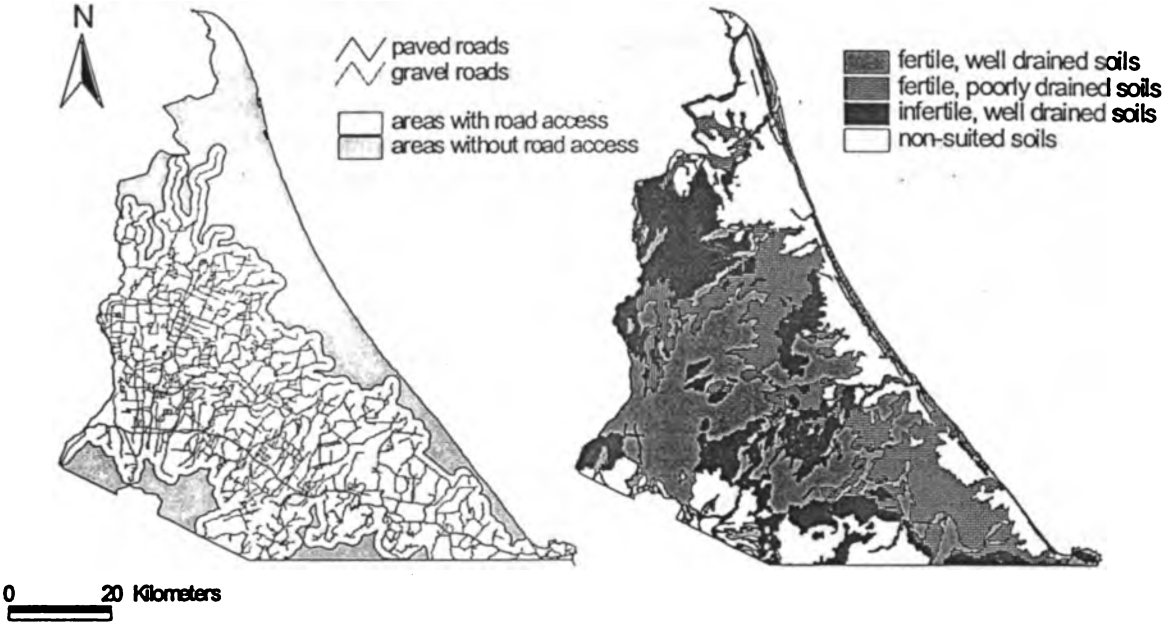
Step 3: Soil characteristics of the three soil types were used in the calculation of land use options by the TCGs. Data exported to the LP model were, per sub-zone: soil and labour resources (Right Hand Side data), and 'product transport cost' and 'labour mobility costs across sub-zones' (Matrix Coefficients).

Step 4. Results of optimizations of the LP model were returned to the GIS in the form of the trade-off variables summed over all selected land use activities per sub-zone: labour employment, physical production, soil nutrient balances, pesticides applied, and nutrient losses.

Step 5: Maps were made of land use and trade-off variables in the NAZ for different scenario runs (e.g. Figures 4 and 5).

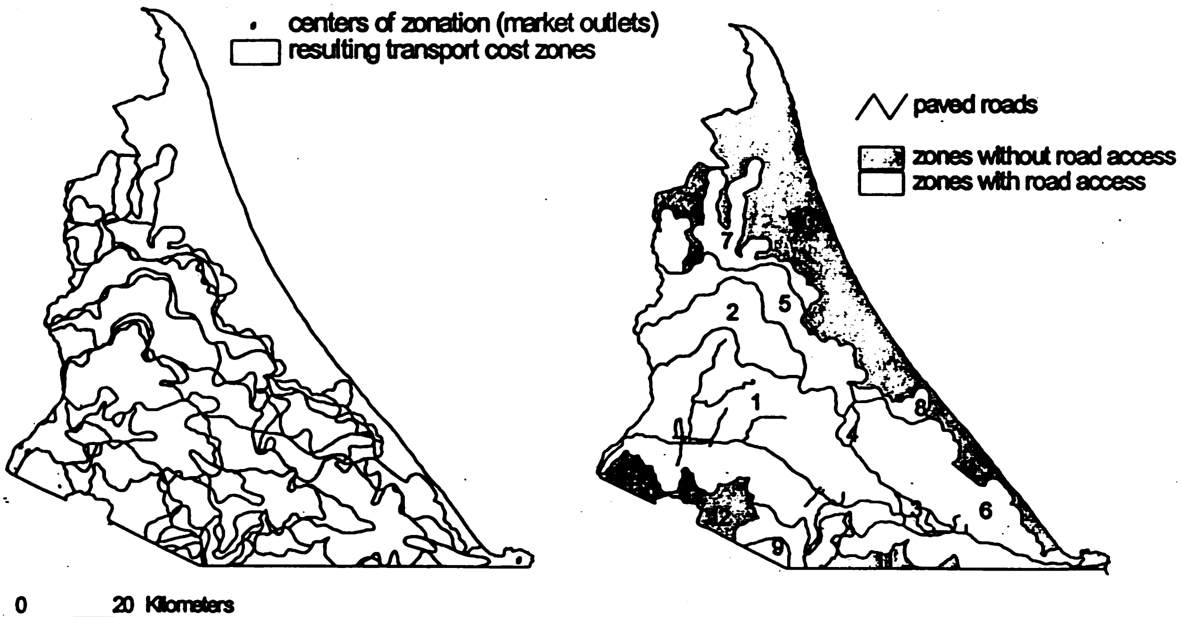
RESULTS AND DISCUSSION

As example, maps are presented here for the trade-off variables 'land used for crops' and pesticide use for the base run and for the severe sustainability run in Figures 4 and 5. In the base run, the percentage land used for cropping is highest in the southern zones and lowest in the northern zones because of increasing transport costs from south to north. In the sustainability scenario, considerable less land is used for cropping than in the base run (Figure 4b). It is noted that in the south, the sub-zones 9 and 12



(a) (b)

Figure 2. Base maps: road infrastructure (a) and soil type distribution (b)..



(a) (b)

Figure 3. Overlay of three transport cost zones (a) and the resulting sub-zone map (b).

which had the highest percentage under crops in the base run, are now completely left unused by crops because of relatively high transport costs. Though these areas lie close to the main road in the NAZ, they have a poor infrastructure (see Figure 2a). The amount of active pesticide ingredients per hectare, averaged over all land used for agriculture for each sub-zone, is given for the base run in Figure 4a. Differences among sub-zones are related to crop types and technologies (data not shown). In the sustainability scenario, the total amount of active ingredients used in the NAZ was restricted to 50% of the base run value. In most sub-zones, the average amount applied per hectare agricultural area decreased in comparison with the base run result (Figure 4b). However, in the central zones 1 and 3, the average amounts per hectare increased with respect to the base run results because of changed technologies in crop production (data not shown). The maps shown in Figures 4 and 5 illustrate the trade-offs between land use for cropping (farmers interest) and environmental pollution (environmentalists interest) per sub-zone and for the NAZ as a whole. Moreover, they visualize so-called 'hot-spots' where local goals (sub-zone) may conflict with regional goals (entire NAZ).

The scenarios executed so far had no implications for the geographic base of SOLUS; steps 2-5 of Figure 1 were executed only once. However, the elaboration of new scenarios might lead to re-redefinition of the geographic base. For example, the road infrastructure is currently poorly developed and some areas in the frontier zone are hardly accessible. SOLUS is ideally suitable to explore consequences for land use options after improvement of accessibility. The addition of new roads or the improvement of the quality of existing ones will lead to a new zonation of the NAZ in step 2, and consequently to new map overlaying and calculation of attribute data such as resource data and transport costs.

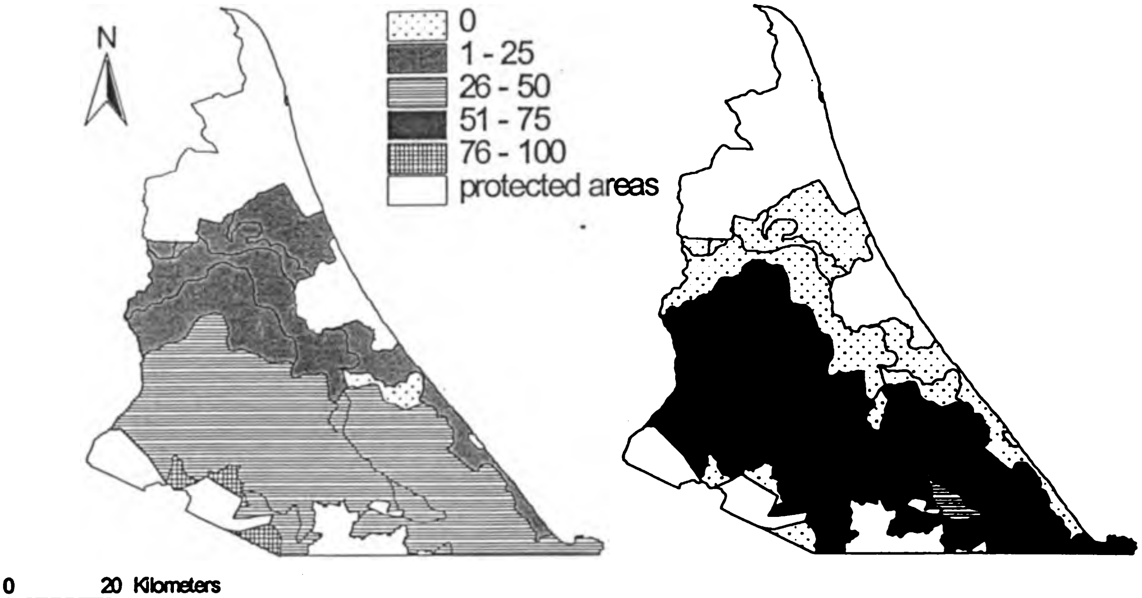
4 REFERENCES

Bouman, B.A.M., R. A. Schipper, A. Nieuwenhuyse, H. Hengsdijk & H.G.P. Jansen, 1998. Quantifying economic and environmental trade-offs in land use exploration at the regional level: a case study for the Northern Atlantic Zone of Costa Rica. Submitted to Ecological Modelling.

Stoorvogel, J.J., 1995. Linking GIS and models: structure and operationalisation for a Costa Rica case study. Netherlands Journal of Agricultural Science, 43: 19-29.

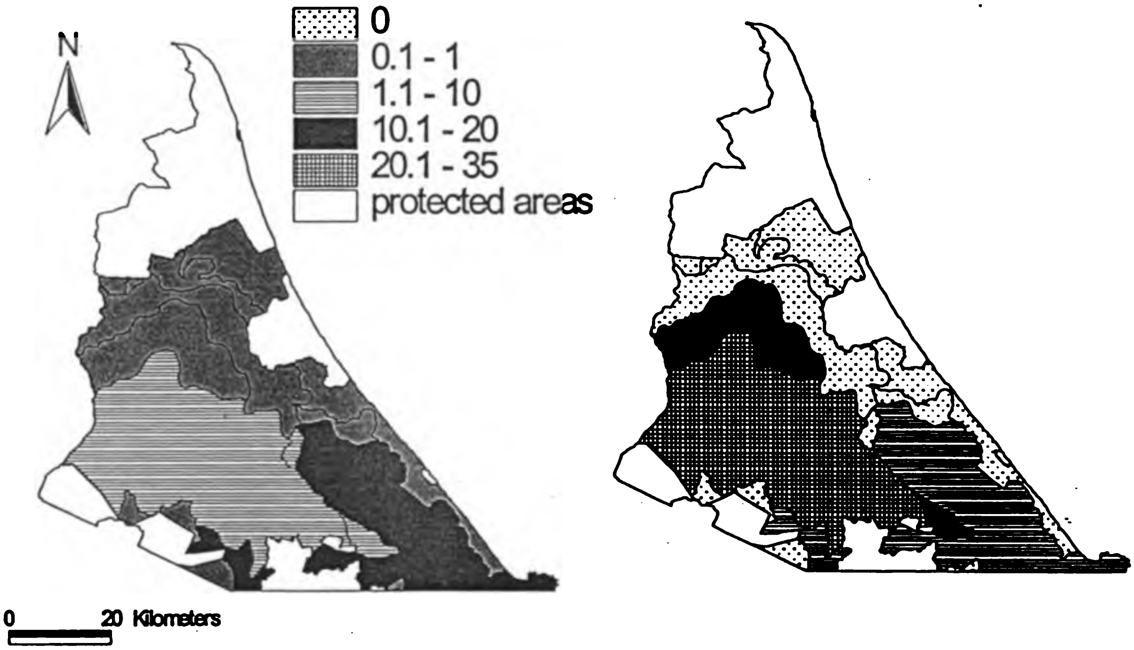
Stoorvogel, J.J., R.A. Schipper & D.M. Jansen, 1995. USTED: a methodology for quantitative analysis of land use scenarios. Netherlands Journal of Agricultural Science, 43: 5-18.

Van Ittersum, M.K. & R. Rabbinge, 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research 52: 197-208.



(a) (b)

Figure 4. Percentage of suited land area under crops (%) in base run (a) and in sustainability run (b).



(a) (b)

Figure 5. Pesticide use (active ingredients kg/ha used land) in base run (a) and in sustainability run (b).