Netherlands Journal of Agricultural Science 43 (1995) 5-18

USTED: a methodology for a quantitative analysis of land use scenarios

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Received 12 October 1994; accepted 19 March 1995

Abstract

Scenarios are a useful tool to study the effects of changes in the socio-economic and/or bio-physical environment on agricultural land use. For the analysis of these scenarios an operational methodology, denominated USTED, has been developed. The methodology is based on a linear programming model in combination with GIS, crop growth simulation models, and expert systems. The data requirements include quantitative descriptions of land use systems and technologies, attribute data on e.g. prices and chemical compositions, and georeferenced data on farms and soils. Sustainability is incorporated in the methodology by a limited number of quantified sustainability parameters. The linear programming model analyses, on the basis of different farm types, the effect of different scenarios on land use. Customized computer software (MODUS) operationalises the integration of the different models. The methodology is illustrated with a case study for the Neguev settlement in the Atlantic Zone of Costa Rica.

Keywords: Costa Rica, GIS, land use scenarios, linear programming models, sustainability

Introduction

Agricultural land use planning may be based on techniques like land evaluation (Anonymous, 1983), farming systems analysis (Beets, 1990) or a combination of these two (Fresco *et al.*, 1992). These techniques work at specific levels of detail which are related to the hierarchical level in the agriculture sector with national, regional, sub-regional and farming systems. Land evaluation typically studies possible land uses for each of these systems. Farming systems analysis is restricted to the farm level and focuses on the specific cropping systems and their interactions. A combination of land evaluation and farming systems analysis (LEFSA, Fresco *et al.*, 1992) may compensate for the drawbacks of the individual procedures. A complementary approach for the development of alternative land use plans is the use of scenarios, a technique which can be used at different levels of analysis: farm level (Sharifi, 1992), regional level (Despotakis, 1991), or on a supra-national level

(Anonymous, 1992). A land use scenario is defined as a set of hypothetical changes in the socio-economic and/or bio-physical environment. The analysis of land use scenarios in the present context comprises the study of the effects of these changes on agricultural land use. At the sub-regional level (e.g. settlement or municipality), the analysis of the agricultural sector can be approached from a regional or national perspective, or from a farming systems point of view. The farming systems approach, which will be discussed in the present paper, deals with farms and their production conditions in specified locations in a sub-regional setting. The regional and national contexts are included through a number of boundary conditions. Specific emphasis on the agricultural sector in a region is justified for those regions where agriculture forms the main occupation of a large part of the population and agriculture is the major form of land use.

Farmers are the final decision makers in agricultural production, selecting cropping systems on the basis of their resources and goals, while being conditioned by the socio-economic environment. The total output of the agricultural sector thus depends on the actual selection of croppig systems and livestock systems by the individual farm households. In the present context each of the cropping systems and livestock systems is defined as a combination of a land unit with a land use type and include specific quantitative descriptions of the technology and corresponding input and output. These land use systems with a specified technology are denominated LUSTs (Jansen & Schipper, 1995). LUSTs fall within the definition of land use systems of FAO (Anonymous, 1983), but the definition includes quantitative descriptions of the operations. The technology is described by the operation sequence coinciding with the specific management of the LUST. The output of the LUSTs consists in this context of (a) types and quantities of products, and (b) negative or positive contributions to determinants of the sustainability of agricultural production, thereby generating off-farm effects at the (sub-) regional level and affecting future production possibilities.

During the last decade an increasing number of simulation models have been developed to describe and simulate agro-ecological processes at different levels of detail. Simulation models describe crop growth as a function of soil and climate (Van Keulen & Wolf, 1986); agricultural household models describe the farm as a decision making unit (Sing *et al.*, 1986); and linear programming models can be used to analyse different land use scenarios (Hazell & Norton, 1986). In addition, a geographic reference in the analysis became possible through the use of a Geographical Information System (GIS) which can be linked to the different models (Stoorvogel, 1995). While recognizing the strengths and the limitations of the different models, they are integrated into a tool for the analysis of land use scenarios. The resulting methodology denominated USTED (*Uso Sostenible de Tierras En el Desarrollo* or sustainable land use development) has been developed at the Atlantic Zone Programme of the Wageningen Agricultural University in cooperation with the Center for Research and Education in Tropical Agriculture (CATIE, Costa Rica) and the Ministry of Agriculture and Animal Production (Costa Rica). The methodology integrates different simulation models (for e.g. crop growth and farming systems) for a geo-referenced analysis (using a GIS) of land use scenarios and is illustrated with a case study for the Atlantic Zone of Costa Rica.

The USTED methodology is developed for the evaluation of effects of external factors (e.g. labour availability and market prices) on land use at the sub-regional level. Sustainability aspects of land use can be expressed by a number of quantitative criteria, thus presenting a pragmatic approach to the concept of sustainability. The output of USTED is the selection and distribution of land use according to a goal and a set of constraints.

Methodology

Background and objectives

The agricultural sector of a subregion is typically influenced by the surrounding region and the national level. This may occur in a passive manner through market and price developments, but also active interference may take place. A wide range of incentives and regulations are available for the policy maker (Lutz & Daily, 1991), and perhaps one of the most frequently used tools is price policy (e.g. Guardia *et al.*, 1987). These tools are mostly used to influence farmers' decisions regarding their selection of land use systems. Although, in general, policies are made at the national (or sometimes at the regional) level, their effects are felt at, and can be evaluated for, a specific sub-region. The effects of these measures are often confounded by the behaviour of farm households (Singh *et al.*, 1986). Linear programming models have shown to be suitable to study the effect of changes in the socio-economic environment and bio-physical environment on agricultural land use (Hazell & Norton, 1986).

USTED aims at the analysis of the effects of changes through e.g. policies on agricultural land use in a sub-region. Each set of changes is translated into a scenario definition. To study the effect of different scenarios on agricultural land use, a methodology has been developed on the basis of a linear programming model. The methodology maximizes total net farm income in a sub-region on the basis of a set of constraints for different farm types and the sub-region. The farm types are defined on the basis of farm size and the soil distribution on the farm. Policy makers become increasingly aware of the environmental effects of agricultural production, and sustainability is increasingly becoming a policy objective (Farshad & Zinck, 1993). Therefore, sustainability indicators have to be included in the analysis.

Structure of the methodology

The USTED methodology is defined by a number of sequential steps (Figure 1) consisting of (1) data collection, (2) the definition of the scenario, (3) analysis of LUSTs, (4) solving the optimisation problem, and, (5) the presentation and interpretation of results.

1) Data collection is aimed at three different data sets with information on LUSTs, attributes, and farm types respectively. Information on land use systems with their

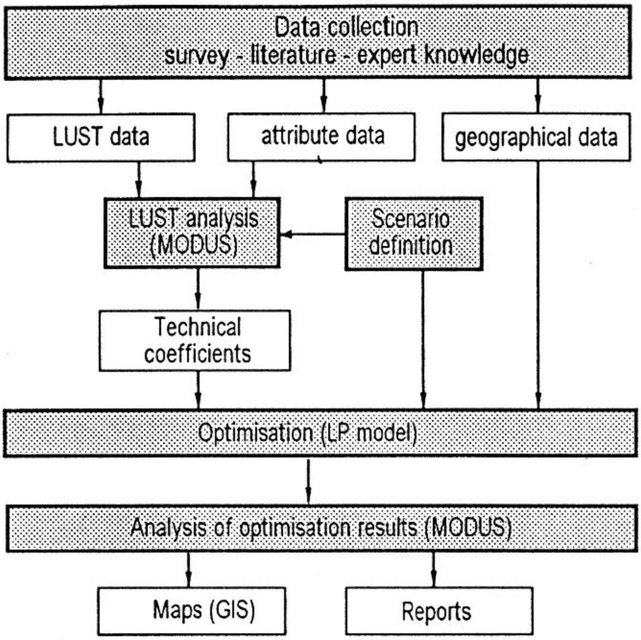

Figure 1. General framework for the USTED methodology.

technology are stored in the LUST database which, for each LUST, include a reference to a certain land unit and a quantitative description of the operation sequence (Jansen & Schipper, 1995). Depending on the aim of the analysis both actual and alternative LUSTs can be described. Expert knowledge (including crop growth simulation models) are necessary to estimate the outputs for the alternative land use systems . In the operation sequences, reference is made to quantities of inputs (e.g. fertilizers and seeds) and of outputs (e.g. products). Additional information on these inputs and outputs (e.g. prices and chemical composition) is stored in the attribute database. The methodology includes the farm level through a number of farm types, which are generalisations of the relatively large amount of farms in a region. The geographic data on farm types include information on the number, sizes, location and the soil types of these farm types.

2) The scenario definition translates changes in the socio-economic or bio-physical environment into technical coefficients, constraints and an objective function for the linear programming programming model. Typically, the analysis is preceded by a base scenario, with which the alternative scenarios are compared. The base scenario can contain present values of the technical coefficients and actual constraints which farmers encounter in their land allocation decisions.

3) The analysis of LUSTs is aimed at the calculation of the technical coefficients for the linear programming problem. It includes data on resource use by the different LUSTs (necessary for the different constraints on resource availability), but also the net return of the different activities (included in the goal function). If sustainability is included in the analysis, a restricted number of parameters influencing the sustain-

ability of the LUST must be selected and quantified. These parameters should adequately reflect constraints of sustainability in the study area, and it should be possible to quantify them. Additional models are used to quantify the sustainability parameters (e.g. erosion or soil nutrient balances).
4) The optimization takes place through a linear pogramming model, which is based on a set of technical coefficients structured in an objective function and a set of constraints. The objective function is defined as maximisation of total net income of the sub-region, but may be defined in alternative scenarios as the minimisation of biocide use or nutrient depletion. The constraints describe the availability of resources (e.g. land and labour) and restrictions on the sustainability parameters. They describe the limitations that farmers might face in their land allocation decisions and may originate at either the level of the farm or at the sub-regional level. The use of labour, for example, is typically restricted by the amount of labour available on the farm and by the availability and price of external labour in the sub-region. Different land use scenarios have different sets of constraints, prices or availability of resources. The results of the linear programming model are a selection of LUSTs for each of the farm types within the sub-region, with its resulting farm economics (including costs of inputs and labour and the value of production), together with the values of the sustainability parameters.
5) The analysis of the scenario results yields reports that summarize the optimisation results. Subsequently, the GIS visualizes the scenarios results to enable a quick interpretation. In addition, the GIS enables a georeferenced analysis which may especially be necessary for sustainability parameters, where e.g. concentration of pollution may be extremely important. The interpretation of the results is crucial because the scenario description is unable to fully describe the actual situation in the sub-region. Analysis of the results might lead to an iterative process where the optimization model is run again with an adapted scenario.

Operationalisation

For the operationalisation of the methodology a software package, denominated MODUS (MOdules for Data management within the USTED methodology) has been developed. MODUS transforms databases from one of the models or tools to the specific requirements of others. For example, the technical coefficients in the linear programming model include data (like monthly labour use), which as such are not in the LUST descriptions. MODUS calculates the data on the basis of the LUST descriptions and exports them in the appropriate format to the linear programming model. For specific variables like the soil nutrient balance, external models are used. MODUS allows a query on the LUST database to select LUSTs to be included in the analysis. This makes it possible to include e.g. only actual LUSTs, or LUSTs which, according to the soil nutrient balance or biocide index, fulfil some sustainability criteria. The optimisation takes place through the simplex method in the OMP software package (Anonymous, 1993b). OMP reads the datafiles generated by MODUS and writes the linear pogramming results to a new datafile which is read by the report generator of MODUS.

Results

The USTED methodology has been applied at the sub-regional level for the Neguev settlement located in the northern part of Limon province of Costa Rica (Figure 2). The settlement comprises 4675 ha and is subdivided in 307 farms of between 10 and 17 ha each. The elevation of the settlement varies between 10 and 80 m above sea level, in a region with a humid tropical climate characterised by a rather evenly distributed mean annual rainfall of 3630 mm and an average air temperature of about 26°C. Soils in the area comprise (1) young alluvial, well-drained volcanic soils with a relative high fertility (Inceptisols and Andisols), (2) relatively old, well-drained soils developed on fluvio-laharic sediments with a relative low soil fertility (Oxisols and Inceptisols) and (3) young, poorly drained volcanic soils with a relative high soil fertility (Entisols and Inceptisols) (De Bruin, 1992). During the last 40 years, 68%

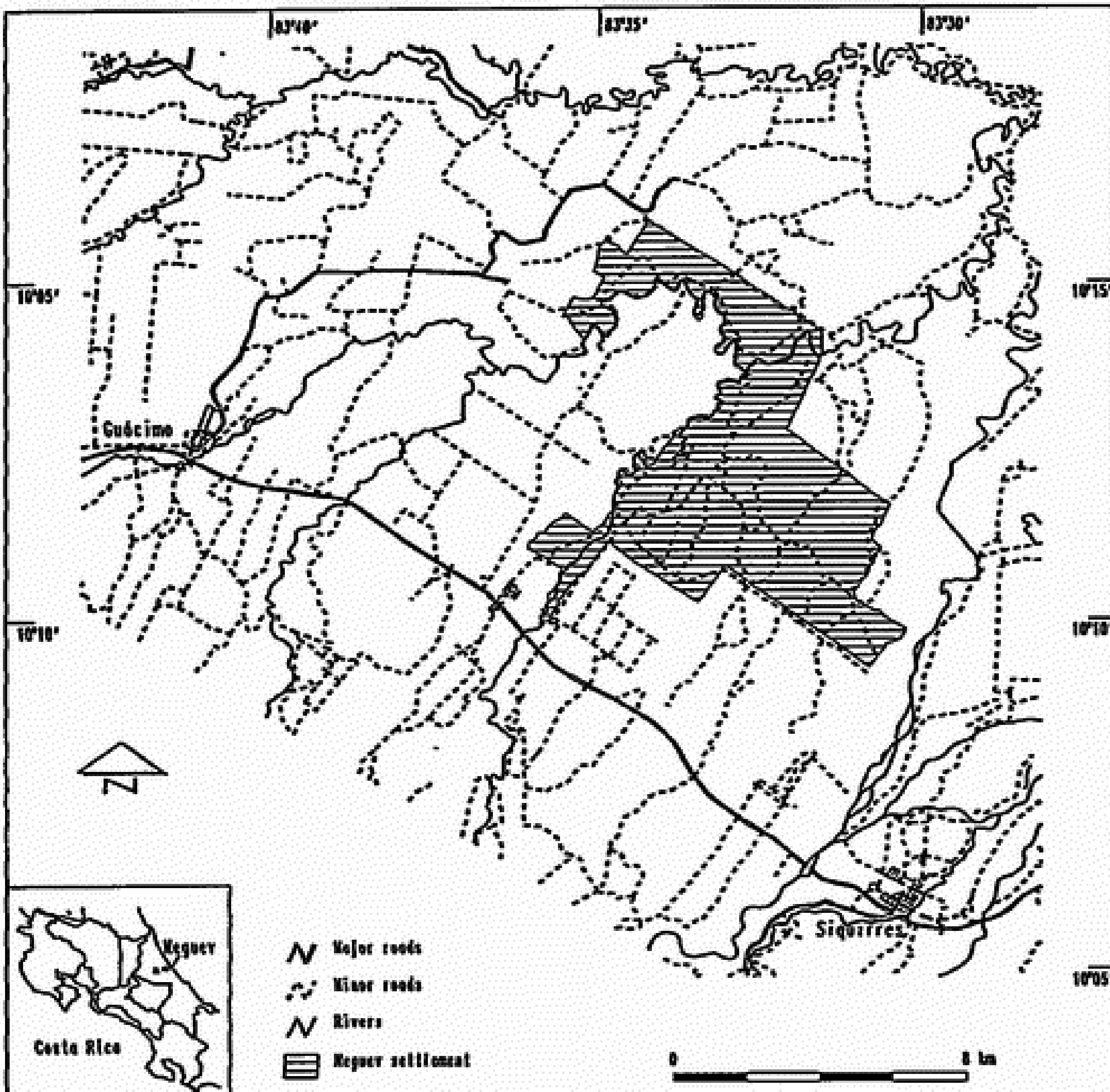

Figure 2. Location of the Neguev settlement.

of the settlement was deforested and land use changed rapidly. Actual land use is dominated by extensively used pasture with smaller areas under annual crops (maize, red pepper, tubers and roots) and perennial crops (palm heart, plantain and fruit trees).

Database

Operation sequences can be based on different sources of information. In the Neguev case, farm surveys were used for the description of actual LUSTs, i.e. LUSTs which were present in the Neguev settlement at the time of the survey. Alternative LUSTs were defined on the basis of literature, expert knowledge including simulation models, and field experiments. The number of LUSTs with the range in alternative technologies included in the analysis governs the quality of the results for the scenarios. As each LUST is determined by a land unit, a land use type and a specific technology a large number of alternative LUSTs has to be described. In the case of the Neguev settlement three land units and eight land use types (pasture, maize, plantain, pineapple, cassava, palm heart, tree plantations, and forest) are identified. Relevant combinations are selected on the basis of historic and actual occurrence and future production possibilities. On average 8 different technologies for each combination are described with different levels of labour, fertilizer and biocide inputs resulting in 124 LUSTs. Attribute information of inputs and outputs is based on field surveys, literature surveys and field experiments. Only a limited number of farm types can be included in the linear programming model. In the case of the Neguev, a cluster analysis on the physical potential for agricultural production of the 307 farms resulted in five different farm types (Schipper *et al.*, 1995). The physical potential is defined by the size of the farm and the different land units. It is the result of an overlay of the map with the location of the farms (Anonymous, 1981) and the 1: 20.000 soil map (De Bruin, 1992) as presented in Figure 3.

Optimisation

For the case study, the following variables are included in the linear programming model: average monthly labour figures, annuity of yearly input costs, the value of the production, labour use, soil nutrient balances and the biocide index. Constraints for the availability of the land and labour resources are included. Labour is split in own labour and off-farm work and the latter can be on other farms or on banana plantations. Yearly input costs, the value of production and labour are included in the objective function as net income. The total net income of the five farm types is maximized. In addition, two sustainability parameters were selected for the Neguev: 1) the soil nutrient balance and 2) a biocide index. Yearly average soil nutrient (N, P and K) balances for the LUSTs are calculated on the basis of an adapted version of the NUTBAL model (Stoorvogel, 1993, Jansen *et al.*, 1995). The biocide index is an indication for the total use of biocides per LUST on the basis of their active ingredients, toxicity and half life time (Jansen *et al.*, 1995).

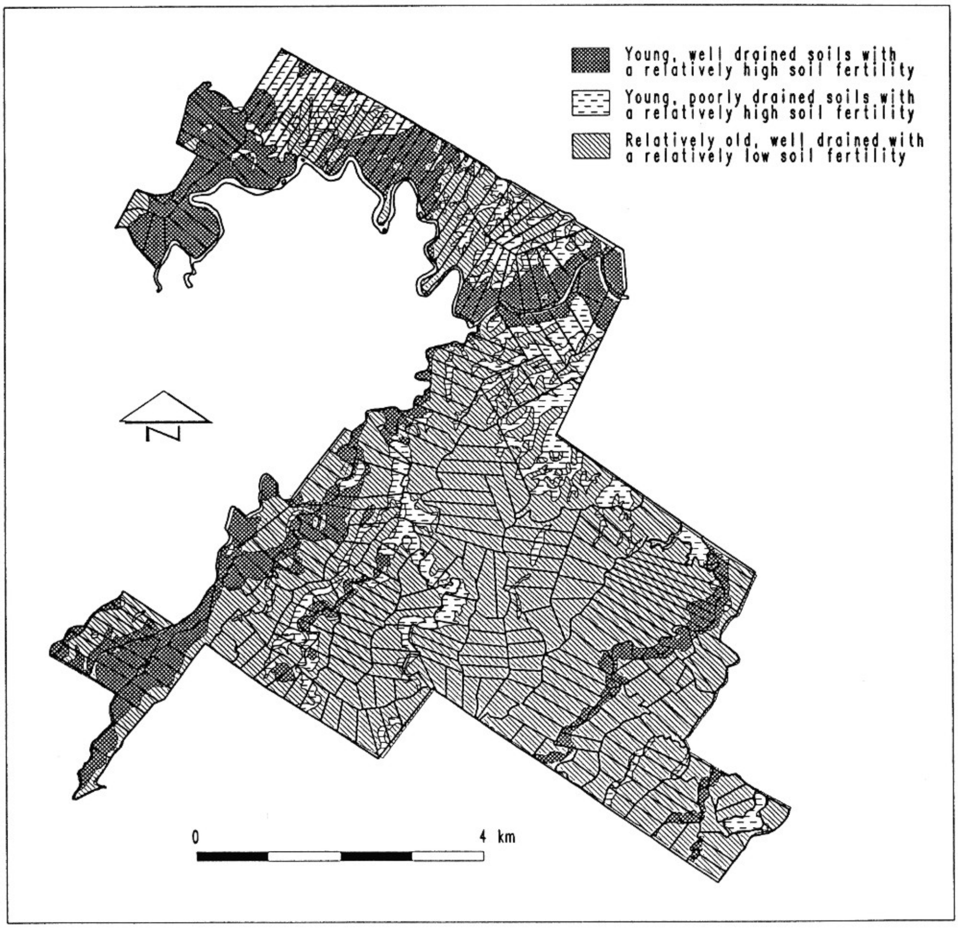

Figure 3. Soils and farms in the Neguev settlement.

Scenarios

In the present context the results of two scenarios will be elaborated: a base scenario, defined on the basis of the actual availability of resources and present prices of inputs and outputs, and a second scenario which studies the effect of a reduction in the palm heart price. Due to the fast expansion of the palm heart area in the Atlantic Zone of Costa Rica, it is likely that prices will drop. The effect of a 50% reduction of the palm heart price is calculated. More scenario results of the USTED methodology are presented in Schipper *et al.* (1995).

In the base scenario net farm income is maximized with limitations on land and labour availability for the different farm types. The LP model selects palm heart as the main crop covering almost 82% of the area. Although at present palm heart occupies a much smaller area in the settlement, its area is rapidly expanding. One of the

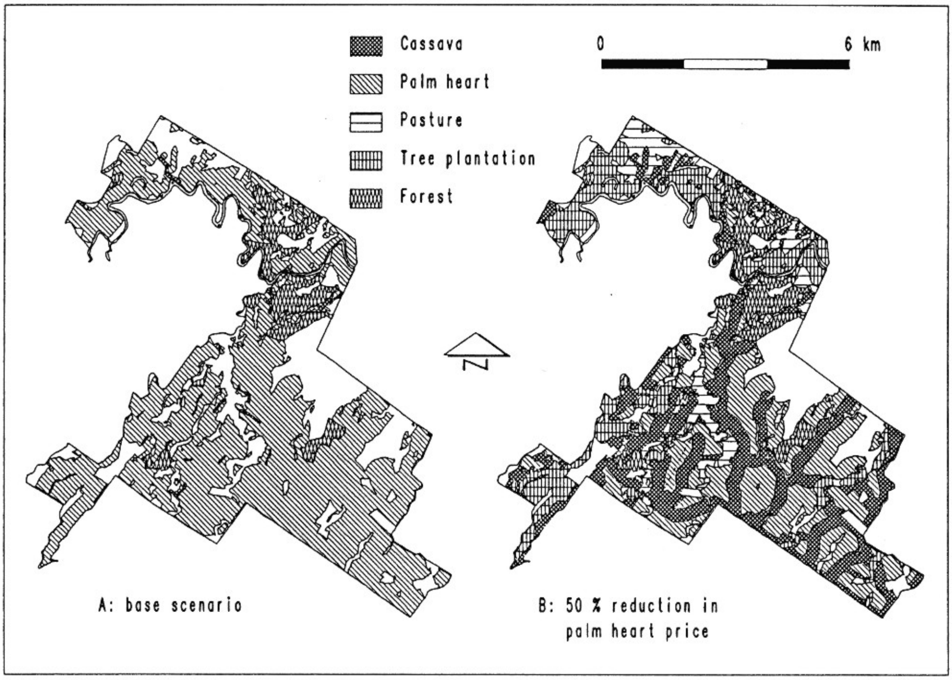

Figure 4. Results for two alternative land use scenarios for the Neguev settlement: the base scenario and the scenario with a 50% reduction in the palm heart price.

main constraints for the expansion of the palm heart is the lack of cash flow for the two years following planting. In this phase, no capital constraints were included in the model.

In the palm heart price scenario the price of palm heart is reduced with 50%. As shown in Figure 4, the model indicates significantly less palm heart, than in the base scenario, and large parts of the settlement are under cassava, pasture and tree plantation. Compared to the base scenario, net farm income in the region is 26% lower.

Discussion

Literature shows several methodologies, where land use systems are described and alternative land use scenarios are evaluated on the basis of a linear programming model and a geographical information system. In the case of Veeneklaas (1990) or Despotakis (1991), linear programming models are used for the analysis of regional agro-technical possibilities, whereas for Anonymous (1992), similar objectives played a role at the supra-national level. In both studies the farming systems were not taken into account, unlike the USTED methodology. However, for the analysis of agro-technical possibilities this is not directly necessary. The USTED methodology is, on the other hand, focused on the analysis of land use scenarios and its effects on the natural resources. A similar procedure on farm level is followed by Sharifi (1992). One of the main restrictions of each of these models is that they are not dynamic. A dynamic approach is proposed by Kruseman *et al.* (1995). One of the main restrictions of that particular model is the lack of geo-reference, which does not allow specific analysis of a number of sustainability criteria. Specific problems coinciding with changes of the geo-referenced basis and changes from one farm type to another, will have to be dealt with. However, the above described procedures are only tools in the process of land use planning. Specific combinations of procedures may lead to an additional value of the combined effort. Procedures such as described by Kruseman *et al.* (1995) are complementary to the USTED methodology, specifically dealing with the regional level. Another set of tools such as those provided by different decision support systems (e.g. Del Risco *et al.*, 1988) may improve the methodology. Complementation in these cases may be preferred above integration as a combined methodology is likely to function as a black box.

Limitations of the methodology

The USTED methodology works under a number of assumptions:
(1) regional land use does not influence product prices and the availability of resources other than labour and land, (2) sustainability can be determined by factors that can be quantified and determined at the field level (in the case of the Atlantic Zone: nutrient depletion and biocide use), (3) variation in soils and farms can be described by a limited number of main soil groups and farm types, (4) farms can be classified on the basis of their potential for agricultural production, in terms of size and soil types, and (5) farms are considered to be stable entities, i.e. without changes in size and number.

USTED provides possibilities to evaluate land use scenarios at a sub-regional level, where the region is not treated as one farm, but differences between farms are included. However, it should be realized that only one overall goal function is maximized, namely the total net income for the sub-region, which is the sum of the net incomes of the individual farm types. Lower net incomes for one farm type may occur when the farm income of others increases. The farm level is included in the regional level with a number of regional constraints which include total labour availability and possibilities for off-farm work.

Objectives of the methodology are similar to those of many land use planners. Limitations, however, occur due to the vast data collection efforts which are necessary and the expert knowledge required to interpret the results. The methodology does not give one simple answer to its user, but rather provides for the possibility to evaluate scenarios whose results have to be analysed. The assumptions and limitations of the methodology should always be kept in mind during interpretation of the results. For example, in the case of extremely high productions of one product, its price can be expected to decrease. However, this would be in contrast with the assumption that prices are fixed. With increasing importance of a (sub)region in the market-share of agricultural products, it becomes more important to evaluate the effects of this assumption.

Applications

Although the USTED methodology was developed by a multi-disciplinary team of researchers without a demand from potential users, it is a potentially useful instrument for any organisation dealing with land use planning. Even though USTED in itself is not a planning tool, it supports agricultural planning. Possible users within the Costa Rican context include the following:

(1) In the Atlantic Zone of Costa Rica, the Costa Rican Institute for Agricultural Development (IDA) manages and distributes land in agricultural settlements, including the Neguev settlement, which has figured as the case study for the USTED methodology. Critics of IDA argue that, as most of the agricultural settlements are located on infertile soils with inadequate farm sizes, farming has a low potential. This is supposedly one of the main reasons why farmers sell their land or start working off-farm. IDA provides support to the farmers by training, extension, credit and legal advice (De Vries, 1992). The USTED methodology may help to determine more specifically how the extension and credit can be directed. In addition it may indicate the productive potential of a certain settlement.

(2) Disciplinary studies may yield data on alternative management practices to increase the sustainability of agricultural production. Such studies, however, typically lack data to evaluate the practices in a regional context and as a consequence, are unable to determine the potential for adoption of alternative practices. In the USTED methodology, alternative practices may be translated in alternative LUSTs and be evaluated for different farm types.

(3) Lutz & Daily (1991) identified a large number of possible incentives and regulations which might affect land use in Costa Rica. The effect on agricultural land use of these policy incentives may be evaluated with the USTED methodology. Schipper *et al.* (1995), for example, analyse the effect of increasing prices of biocides on their use in the Neguev settlement. To quantify and evaluate the effect of this kind of measures, USTED may be a useful tool.

Date needs

Like any analysis of the agricultural sector, USTED requires a considerable amount of data at the farm, sub-regional and regional level. Local institutes may not have the necessary resources to collect the data needed. Existing data, however, may provide at least part of the necessary database. Minimum data needs for the USTED methodology are:

- A general purpose soil survey. At the farm level most farmers have insight in the general geographic distribution of the main soil types. At the sub-regional level the required semi-detailed soil map may be available, for example in cases of agricultural settlements, and irrigation schemes.
- Numbers, sizes and soil types of farms.
- Quantitive descriptions of the principal LUSTs in the area and the corresponding attribute database.
- Insight in the farming systems, for example data on labour availability.

- Data on the region for detailed descriptions of the constraints and the alternative land use scenarios.
- Insight in a number of sustainability parameters to enable a quantification of these parameters for each of the LUSTs.

The flows of (disciplinary) data into common inter-disciplinary databases is regulated by MODUS, thereby integrating different disciplinary models in the methodology.

Sustainability aspects

Many definitions for sustainable development and the sustainability of agricultural production exist in the literature (Anonymous, 1993a; Kruseman *et al.*, 1995; Lélé, 1991). Pearce & Turner (1990) propose a definition of sustainable development which involves maximising the net benefits of economic development, subject to maintaining the services and quality of natural resources over time. This implies that (1) renewable resources are utilised at rates less than or equal to the natural rate at which they regenerate, (2) waste flows to the environment are kept at, or below, the assimilative capacity of the environment, and (3) the efficiency with which non-renewable resources are used is optimised, subject to substitutability between resources and technical progress.

Linear programming techniques are used to optimise resource use given a certain objective, thus striving for maximum efficiency. Effects of substitutions of e.g. biocides by labour can be traced via shadow prices of constraints and via sensitivity analysis. In USTED, the notion of 'technical progress' (towards a more productive use of resources) is part of the analysis: for each land use system several sub types are defined according to different forms of technology. In the optimal solution the most efficient technologies (i.e. LUSTs) are chosen, and thus the optimum resource (land, labour and capital) use is achieved in view of all options and constraints given a specific objective function.

In an operational way, USTED allows five ways to incorporate sustainability, which in our case is determined by nutrient depletion and biocide use:

(1) At the field level an ex-ante evaluation of the LUSTs may take place. The nutrient balance or the degradation of soil physical characteristics can be included. For example, one might evaluate a certain land use scenario only with LUSTs that have positive nutrient balances (as by Veeneklaas, 1990).

(2) In the linear programming model, constraints can be defined for nutrient depletion and biocide use. One might define the constraints according to the rate of natural regeneration (in the case of soil nutrients) and the assimilative capacity of the environment (in the case of biocides). This may e.g. be operationalised by a government restriction on the use of biocides. The determination of specific threshold values can be arbitrary as the direct and indirect effects of e.g. biocide use are difficult to estimate.

(3) The sustainability criteria can be included in the objective function. Fot example the efficiency with which non-renewable resources are used may be optimised. This might e.g. comprise the minimisation of biocide use to minimize a possible coincid-

ing loss of bio-diversity, a non-renewable resource.
(4) A post model evaluation may take place at the farm or regional level, where the effect of alternative scenarios on the sustainability criteria can be determined. It is checked whether a certain change directs agriculture to a more sustainable use of its resources. An example may be the effect of changes in the palm heart price on the depletion of nutrients (Schipper *et al.*, 1995). The GIS may play an important role to visualise the implications of the results, e.g. where concentrations of contamination take place.
(5) A last option is to define long-term LUSTs, where the effect of changes in sustainability criteria on production is included in the LUST definition. Although theoretically this may be one the best options, data availability does not allow the implementation of such LUSTs in an operational way. It requires good insight in the effects of the sustainability criteria on the agricultural production. Long-term LUSTs need specific descriptions for different crop rotation leading to a large number of LUSTs, which all need their quantitative descriptions. Time and data restriction as well as restrictions in the size of the linear programming model do not yet allow this approach.

Conclusions

Common databases and coordination of data flows between disciplinary models is one of the prerequisites for inter-disciplinary research. The USTED methodology provides a useful tool to evaluate land use scenarios on a sub-regional level.

The integration of different levels of analysis (in the case of USTED the farm level with the sub-regional level) can be based on the use of similar variables at both levels. On the basis of these variables, constraints on farm and regional level can be included in the linear programming model.

Operationalisation of sustainability can take place on the basis of a number of quantified indicators. For each LUST these parameters can be assessed by adequate modelling, after which the results can be used as variables in the linear programming model. This implies that for these parameters constraints on both farm and sub-regional level can be included.

Acknowledgements

The methodology is developed in close cooperation with the working group Costa Rica of the Wageningen Agricultural University, which is greatfully acknowledged for the fruitful discussions. Several years of more disciplinary research preceded the development of the methodology, which partly forms the roots of USTED. Thanks are due to everybody involved with this research. Hans Jansen (Atlantic Zone Programme) is acknowledged for commenting on earlier drafts of the article.

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