Netherlands Journal of Agricultural Science 43 (1995) 61-82

Using sustainability indicators in agricultural land use analysis: an example from Costa Rica

D.M. JANSEN[1], J.J. STOORVOGEL[1] AND R.A. SCHIPPER[2]

[1] Atlantic Zone Programme, Apartado 224-7210, Guápiles, Costa Rica
[2] Department of Development Economics, Agricultural University Wageningen, Hollandseweg 1, NL-6706 KN Wageningen, The Netherlands

Received 12 October 1994; accepted 23 April 1995

Abstract

A methodology to analyse land use is applied to the Neguev settlement in the Atlantic Zone of Costa Rica. The methodology comprises a linear programming model, a geographic information system, and a customised data management tool. While options for land use are described at the field level, the methodology allows for analysis of land use at the field, the farm and the regional level. The various steps involved in the operationalisation of the sustainability concept are described. Selection and quantification of the sustainability indicators require some assumptions, affecting the period for which the analysis can assumed to be valid. The possibility to use nutrient balances and biocide indices as quantitative indicators of sustainability of agricultural land use systems is argued and demonstrated for the Neguev settlement. Some limitations and advantages of the methodology are discussed.

Keywords: biocide index, land use systems, nutrient balance, quantitative land use analysis, spatial distribution of land use

Introduction

The term 'sustainability' is much in vogue at present, with many definitions in the literature (Anonymous, 1993; Lélé, 1991). Practical implementation of 'sustainability' as a criterion for land use, however, has been hampered by the vagueness of these definitions and by the resulting lack of measurable quantitative indicators (Niu *et al.*, 1993). A long list of indicators can be developed to account for all conceivable factors influencing sustainability of land use (De Camino & Müller, 1993), and practical implementation might well be hindered by a desire to include all these indicators in order to conserve a 'holistic' vision. For operationalisation of 'sustainability' in land use analysis and planning, however, a clear definition is needed, with a limited number of indicators.

Land use analysis is defined here as the process of evaluating potentials of land use, under well defined changes in biophysical or socioeconomic conditions. This article explores implementation of sustainability criteria in the process of land use analysis, on basis of the definition by Pearce and Turner (1990). They state that sustainability involves 'maximising the net benefits of economic development, subject to maintaining the services and quality of natural resources over time'. Use of this definition requires descriptions of 'benefits of economic development' and 'natural resources'. In addition, instruments should be available to enable 'maximisation' while checking that services and quality are 'maintained'.

The term 'benefits' is not univocal, since improving benefits for one group in society can result in deterioration of benefits for other groups. Effects of land use on the benefits of groups can best be described by quantifiable indicators (Rabbinge & Van Latesteijn, 1992; Spharim *et al.*, 1992), such as (reductions in) biocide use and farm income. Valuing the relative importance of each indicator is a subjective process, especially if the impact of changes in indicator values can not easily be quantified, as is the case when the use of biocides is taken as an indicator for the quality of the environment.

When studying the sustainability of a certain land use, the 'natural resources' that need consideration are those that are affected by this land use, and that in their turn affect this or other land uses. The most important ones can be identified via the rules which Pearce and Turner (1990) give regarding the 'maintenance of services and quality of natural resources':

a. renewable resources should be used at rates less than or equal to the natural rate at which they regenerate,
b. waste flows to the environment should be kept at or below the assimilative capacity of the environment, and
c. the efficiency of use of non-renewable resources should be optimised, subject to substitutability between resources and technical progress.

Regeneration of renewable resources is partially determined by the time and spatial scales of biophysical processes (Fresco & Kroonenberg, 1992). Volcanic eruptions or flooding might restore soil fertility in certain regions. If the period of analysis is much longer than the period of recurrence of these events, soil fertility is not an important indicator for sustainability, whereas it can be for shorter periods of analysis. Frequency, quantity and spatial distribution of waste depositions co-determine whether the capacity of the environment to assimilate those wastes is exhausted.

There is a general lack of information on many of the natural resources and wastes, especially on large scale and long term processes. Future technical progress is unknown. Thus, practical problems arise in the determination of rates of regeneration for natural resources, of the assimilate capacity of the environment for wastes, and of the influence of technical progress on the substitutability for each non-renewable resource. Often, at best educated guesses for these factors can be given. This, however, does not need to hinder incorporation of sustainability in land use analysis, as long as it is realised that the selection and quantification of the sustainability indicators reflect present day knowledge, morals, interests, etc. (Anonymous, 1994). This realisation should be reflected in the time-frame for which outcome of the analysis is expected to be realistic.

Optimisation models, either linear or non-linear, are instruments that allow 'maximisation' of goals. In general terms, these models recognise one or more goal-functions to be maximised by choosing from various options to use certain factors, while quantitative limits can be set to the use of the latter. These limits (constraints in terms of the models) can be used to ensure maintenance of quality and services of the resources, by setting upper limits to the use of renewable resources and to deposits of wastes. Maximisation of the goal-function leads to the most efficient use of factors (including non-renewable resources) through certain constraints on the latter.

This paper presents incorporation of sustainability into a methodological framework, called USTED (*Uso Sostenible de Tierras En el Desarrollo*: Sustainable Land Use in Development; Stoorvogel *et al.*, ,1995). The methodology is developed by the Atlantic Zone Programme (AZP), a collaborative research effort of Wageningen Agricultural University (WAU, The Netherlands), the Center for Research and Education of Tropical Agriculture (CATIE, Costa Rica), and the Ministry of Agriculture and Livestock (MAG, Costa Rica). Examples from the Neguev settlement in the Atlantic Zone of Costa Rica are given to illustrate the different steps that need to be taken for operationalisation of this framework. Advantages and limitations of the methodology are discussed.

Materials and methods

The study area

The Atlantic Zone in the North-East of Costa Rica has a tropical climate, with an annual rainfall of 3500–4400 mm, and an annual rainfall surplus between 1350 and 2550 mm, depending upon location within the Zone. Even the driest period (February to April) generally has a rainfall surplus. In the South-West, the Zone is limited by the ranges of the Turrialba and Irazú volcanoes, in the South by the Talamanca mountain range, in the East by the Atlantic Ocean, whereas in the North it continues into Nicaragua. In the Zone, three major Land Units (LU) have been distinguished (De Bruin, 1992):

1) fertile, well-drained LUs, mainly Andisols and Inceptisols, found only in rather flat areas;
2) fertile, poorly-drained LUs, comprising the aquic subgroup of Entisols and Inceptisols, only in flat areas;
3) infertile, well-drained LUs, consisting of Oxisols and the oxic subgroup of Inceptisols, with slopes generally ranging between 0 and 20%.

Most soils are highly permeable for water and water logging occurs only on soils that have poor drainage due to their physiographic position: in local depressions, or in areas below 20 m above sea-level. Most poorly-drained LUs are not fit for agriculture due to frequent flooding and, if used, they support only extensive cattle ranging. Artificial drainage in some banana plantations, however, converted originally poorly-drained LUs into highly productive land.

The Neguev settlement, located within the Atlantic Zone, comprises 307 farms. These differ in size, showing a large variation in the distribution of LUs over the farm area. In the context of the USTED methodology, these farms have been grouped into five farm types (FT) reflecting the major differences between the farms (Table 1; for details see Stoorvogel *et al.*, 1995 and Schipper *et al.*, 1995).

Methodology

The framework of USTED consists of the following modules:

1. A linear programming (LP) model, to calculate optimal land use given a goal, a set of constraints and a series of technical coefficients reflecting the options for land use. Goal and constraints can include socioeconomic and biophysical aspects, including sustainability indicators.
2. A geographic information system (GIS), to facilitate storage and analysis of spatial data, including geographical distribution of soil types and their characteristics; and to visualise model output in maps.
3. A data management tool (MODUS: MOdules for Data management in USted), to facilitate data transfer with USTED; and to calculate the technical coefficients for the LP model.

In USTED, LP modeling is used since its results are generally easier to interpret than those of (more complex) non linear models (Hazell & Norton, 1986). LP poses, however, limitations to the incorporation of some types of sustainability indicators. Linearity implies that land use can not be described as a function of itself, which precludes calculation of optimal land use over time. This is because land use at a certain moment affects the nutrient pool in the soil, or the population of pests and diseases, which in turn affects the land use that follows. In theory, multi-period models are able to handle sustainability over time, where conditions at the end of each period serve as input to the next period. However, such models require tools (e.g. explanatory crop growth models) that translate the changes in the conditions into effects on all possible land uses. Such tools, however, do not (yet) exist (Dent, 1993), do not provide accurate enough results (Angus *et al.*, 1993), or demand too many data. An alternative is to describe sequences of land uses that implicitly incorporate these interactions. This is possible if only a few land use options exist and thus only a limited number of crop rotations have to be described (e.g. De Koning *et al.*, 1992). For situations where many crops can be grown and crop rotations are not ob-

Table 1. Area per farm type in the Neguev settlement, and its distribution over the Fertile, Well-Drained (FWD), Fertile, Poorly-Drained (FPD) and Infertile, Well-Drained (IWD) LUs.

Farm type	number of farms	Area (ha) total	per farm	Percentage of area per LU FWD	FPD	IWD
1	33	518	15.7	12	60	28
2	4	128	32.1	10	12	78
3	46	621	13.5	52	7	41
4	35	493	14.1	91	3	6
5	189	2477	13.1	6	6	88
Total	307	4236	13.8	23	13	64

vious, this approach becomes practically infeasible, due to the large number of possible sequences. Such is the case for the humid tropical conditions of the Atlantic Zone of Costa Rica. Instead, this paper opts for limiting the time horizon of the analysis to a subjective ten year, while resource use can be limited such that no major effect is expected on land use within this period.

The LP model optimises land use at the regional level, while considering the farm-level by recognising different farm types (FT) in the region (Schipper *et al.*, 1995). Other studies using LP models have either focused on the regional level without taking account of the fact that decision making takes place at the farm level (Spharim *et al.*, 1992; Veeneklaas *et al.*, 1990); or on the farm level, without considering interactions that take place at the regional level (Berentsen & Giesen, 1994). In USTED, the LP model maximises total regional net farm income which is used as proxy for the 'net benefits of economic development'. Net farm income fails to take into account costs and benefits which occur outside the farm boundaries. However, constraints can be set on factors that indicate negative effects of resource use or on the benefits of other users. Many socioeconomic indicators of sustainability are related to farm income, such as levels of schooling, health care, nutrition. As such, these do not have to be included explicitly. By recognising different FTs, a possible skewed income distribution among farms can be indicated. The five FTs in the Neguev settlement (Table 1) vary in production potential due to differences in size and in relative distribution of LUs. For each FT, the model uses technical coefficients, derived from LUST descriptions, as options for land use at the LU level. LUSTs (Land Use Systems at a defined Technology; Jansen & Schipper, 1995) describe the physical input/output relations for a particular land use type (LUT: either crop or livestock), under a particular management, on a particular LU. In the LP model, different FTs can select the same LUSTs for similar LUs. The technical coefficients of each LUST are calculated on basis of its inputs and outputs, and describe each LUST in the terms of objectives and constraints of the LP model. In an ex-ante analysis, these technical coefficients can be compared among the LUSTs. This can be done for different situations, e.g. with different prices for (part of) the inputs.

To include sustainability criteria in USTED, the following steps are taken:

1. Selecting sustainability indicators.
2. Developing methods to quantify the sustainability indicators for the individual LUSTs.
3. Developing methods to quantify the limits to sustainability indicators that appear in the constraints or the goal of the LP model.
4. Adapting the LP model to incorporate these indicators either in the goal or in the constraints.
5. Describing LUSTs
6. Analysing and selecting LUSTs to submit to the LP model.
7. Running of the LP model
8. Analysing the results of the LP model, including the spatial distribution of land use.
9. If the analysis at 8 indicates undesirable results: including other sustainability in9.

dicators, adapting constraints, or formulating alternative LUSTs. Thereafter, the procedure has to be started again from step 1, 4 or 5, respectively.

Steps 1–5 are part of what, in USTED, is called scenario development. A scenario is defined as a given set of conditions (e.g. prices), constraints and objective, which are submitted to the LP model for evaluation.

Results

In the following sections, the above described steps are illustrated with examples from the Neguev settlement.

1. Selection of sustainability indicators

The major causes affecting sustainability should be reflected in the indicators which should be quantifiable as well. This consideration demands a thorough analysis of the conditions in the area of interest, and of the information available. For the Neguev settlement such an analysis led to the selection of two sets of sustainability indicators: balances of N, P, and K in the soil, and an index of biocide use.

Sustainability of agricultural land use comprises two major aspects; i.e. sustainability of the productivity of the agricultural system and sustainability of concurrent nonagricultural uses of land.

Biophysical factors that can influence crop productivity are nutrient and water availability, erosion, soil compaction, and weeds, pests and diseases. In the Neguev, balances for soil nutrients are generally negative for most prevailing cropping systems. With negative nutrient balances, the production potential of the soil declines over time, causing lower yields, or higher costs of fertilisation to sustain a given yield level. Therefore, balances for soil N, P and K, the major nutrients, are taken as one group of sustainability indicators.

Water availability in all LUs is generally sufficient to enable near optimal crop production, due to high rainfall and large water holding capacity of the soils. Thus, water availability is not a suitable sustainability indicator. Drainage improvements for the poorly-drained LUs are prohibitively expensive for small and medium farmers (the focus of the AZP), and no efforts were spent on defining major land improvement operations in the LUSTs for these LUs.

In spite of high levels of rainfall, visible erosion is at present virtually absent in the study area, (Dercksen, 1991; preliminary results of experiments by Rosales, pers. comm.). For land under annual crops this is mainly because of high hydraulic conductivities of the soils, whereas in case of perennials and pastures the permanent cover of the soil is another important factor. Still, some erosion does occur, and although the amount of soil removed from the areas under agriculture is insignificant, the amount of nutrients, especially N, removed from the system can be important, particularly in systems with low external input of nutrients. Effects of (non-visible) erosion on the soil nutrient balances are therefore taken into account. Deterioration of the structure of the land does not occur at present, nor is it expected to occur in the foreseeable future. This is particularly so because increasing the degree of mechanisation is hardly feasible due to the low workability of the soils.

Top soil compaction has been observed in the Atlantic Zone, especially in pastures (Ibrahim, 1994; Spaans *et al.*, 1989). However, no effects on crop and pasture production have been reported, and compaction at present only poses problems where pastures are converted into arable land. The LP model only calculates an optimal situation with a stable land use, where land use in areas under pasture and perennials is not changed, and annuals rotate only over fixed areas. Problems related to conversion of pasture into other land use, therefore, are not taken into account.

Land use can affect the population dynamics of weeds, pests and diseases, which in turn can influence land use by affecting yields at given levels of crop protection measures. The effects of this interaction over time at the field level can be incorporated in the LUST descriptions of perennials and pastures. For example in some plantain LUSTs, build up of nematode populations is prevented through nematicide applications, and absence of these applications in other LUSTs results in yield reductions that progress over time. For annual crops, cropping sequences could be described that limit build up of yield reducing factors in the field. However, while a large number of combinations is conceivable in the Atlantic Zone, problems with build up of yield reducing factors have not been reported for the LUTs under consideration. Consequently, a constant pressure of these factors has been assumed for the annual LUTs. Regional population dynamics of yield reducing factors for a certain LUT can be influenced by its total area in the region. In the USTED methodology, this can only be assessed in the context of an ex-post analysis of the results of the LP model. When calculated land use is thought to affect weed, pest and/or disease pressure, one or more of the following needs to be done, before running the LP model again:

1. adjusting the relevant crop protection measures.
2. describing long-term LUSTs with cropping sequences that limit the build up of yield reducing factors, and submitting only those LUSTs to the LP model
3. imposing constraints on the total area under one LUST or LUT

Indicators of sustainability of concurrent, non-agricultural land uses depend strongly on the nature of these uses. In the Atlantic Zone, these uses mainly include nature conservation and provision of drinking water. The former has been strongly affected by deforestation during the past fifty years (Sader & Joyce, 1988). Nowadays, the major part of the remaining forest is in protected areas, a large part of which consists of swampy areas downstream rivers. In the remote rural areas of the Atlantic Zone, ground water and, in the rainy season, surface water are used for drinking water. Possible environmental effects of agriculture are mainly through changes in water quality, in the form of nutrient enrichment and biocide pollution. The use of herbicides is common in the Atlantic Zone, while large amounts of nematicides and fungicides are used in banana plantations and, probably, in the cultivation of ornamentals and cut flowers. Biocides reach the ground and surface water close to the site of application, as has been shown for the nematicide Ethoprop (Rosales *et al.*, 1994). However, average concentrations of biocides and nutrients in ground and surface water in the Atlantic Zone are very low, due to the large rainfall surplus in the Zone. Bimonthly measurements in a representative major river in the Zone revealed only low levels of biocide contamination (below 0.1 μg l^{-1}; Castillo *et al.*, 1993). On the other hand, temporal and regional concentrations of applications might result in peak loads in rivers and ground water, especially during the dryer months. Only few observations on nutrient load due to agricultural activities are available (unpublished data by De Jong), indicating maximum concentrations of 2.9 mg NH_4^+ l^{-1} in deep wells (>30m) under a banana plantation fertilised with about 400 kg N ha^{-1} $year^{-1}$, mainly as ammonium nitrate. This is well below the critical level of 10 mg NH_4^+ l^{-1} used in Costa Rica for drinking water (Monturiol, 1994). For nutrients, it can be expected that possible effects on 'nature' of changes in concentrations in water will take a long time to be expressed in changes in biomass, population dynamics and biodiversity. It seems reasonable to assume that the actual natural vegetation is well adapted to the naturally occuring flows of nutrients into and out of the system. Natural events cause large amounts of nutrients to be added to the system: after periods with prolonged heavy rainfall (occurring more than once every year), or major earthquakes, large amounts of soil from the volcanic and the Talamanca ranges are transported to the Atlantic Zone, often with considerable amounts of organic matter. During the most recent major earthquake (in 1991, of 7.5 on the scale of Richter), the beaches along the whole Atlantic coast were literally covered with tree trunks originating from the Talamanca range (own observations). This type of major earthquakes occur with a frequency of once in about 40 years in the Zone (Montero *et al.*, 1991), and it seems reasonable to assume that changes in the nutrient fluxes from agricultural areas can be considered negligible in comparison with these natural fluxes. For nutrients, therefore, no attempt is made to include their effect on water quality in the sustainability indicators.

In theory, it is possible to model deterministically the flow of biocides into ground and surface water (Jury & Flühler, 1992; Selim, 1992). In view of the large number of biocides, it is virtually impossible to obtain the data required by these models. Furthermore, little is known about the reaction of human beings and 'nature' to different concentrations of the various toxins, and to varying frequencies and durations of exposure. Even though an exact quantification of the effects of biocides therefore seems impossible, they are likely to be the more pronounced the more active ingredients are used, the longer their activity is in the system, and the higher their toxicity.

Consequently, a biocide index was developed that incorporates these three aspects and that can be used to indicate relative effects of biocide use across different land use systems.

2. Quantification of sustainability indicators at the LUST level

Nutrient balances

To calculate nutrient balances, an adapted version of the nutrient balance model developed by Stoorvogel (1993) is incorporated in USTED. This model determines, for

Table 2. Gross inputs and outputs to the nutrient balances of LUSTs and origin of variation (after Stoorvogel, 1993).

Origin	Gross inputs	Gross outputs
LUST	-- Mineral fertilisers -- Crop residues and organic fertilisers -- Biological N fixation	-- Harvested product -- Leaching -- Volatilisation -- Erosion
REGION	-- Wet and dry deposition -- Sedimentation	

each LUST, the net sum of all inputs and outputs for N, P and K, including the effects of erosion. These sums are divided by the duration of the LUST (in years), to enable comparison of LUSTs with different durations in the field. Inputs and outputs are either determined completely regionally, or at least partly by LUST-specific characteristics (Table 2). Estimates for erosion, leaching and volatilisation refer to the entire cropping season, and as such are not detailed enough to calculate temporal patterns of concentrations of nutrients in surface and ground water.

Negative N, P and K balances are found for about 60, 30 and 90%, respectively, of the 122 LUSTs described for the Neguev. N and P balances are positively related to higher mineral fertiliser rates, whereas K shows a more diffuse relation (Figure 1). Higher fertiliser applications thus result in a more sustainable land use if only land productivity is taken into account. However, LUSTs with higher mineral fertiliser rates do not necessarily generate higher income (Jansen & Schipper, 1995), and may therefore be less attractive in economic terms. Furthermore higher fertiliser rates provoke higher losses of N, P, and K to the environment (Figure 2), with losses defined as leaching plus volatilisation for N, and leaching for P and K.

Biocide index

To enable comparison of the different biocides, the following biocide index is calculated for each LUST:

$$\mathrm{BILU}_L = \frac{1}{\mathrm{Y}} \sum_{a=1}^{n} \sum_{b=1}^{m} \mathrm{A}_{L,a,b} * \mathrm{AI}_b * \mathrm{TOX}_b * \mathrm{DUR}_b$$

with
BILU_L = biocide index of LUST L; Y = duration of LUST L in years; n, a = total and a^{th} number of biocide applications in LUST L; m, b = total and b^{th} number of biocide used at application a in LUST L; A = amount of commercial formulation of biocide b at application a; AI = fraction active ingredient in the commercial formulation of biocide b; TOX = indication of toxicity of biocide b, related to the WHO code (Table 3); DUR = indication of duration of existence of toxin of biocide b in the system. Here taken as the squared root of the duration in days, to take account of the fact that

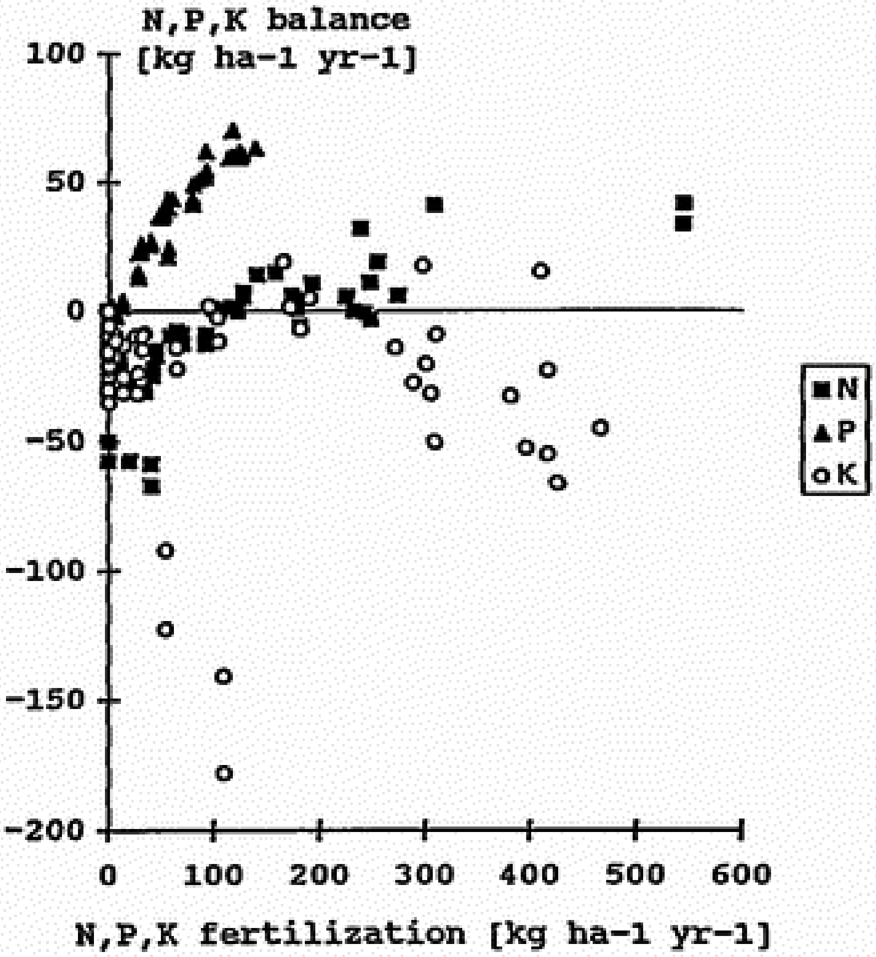


Figure 1. Balances (in kg ha^{-1} year^{-1}) of N, P and K in relation to fertiliser rates (in kg ha^{-1} year^{-1}), for all 122 LUSTs developed for the Neguev settlement.

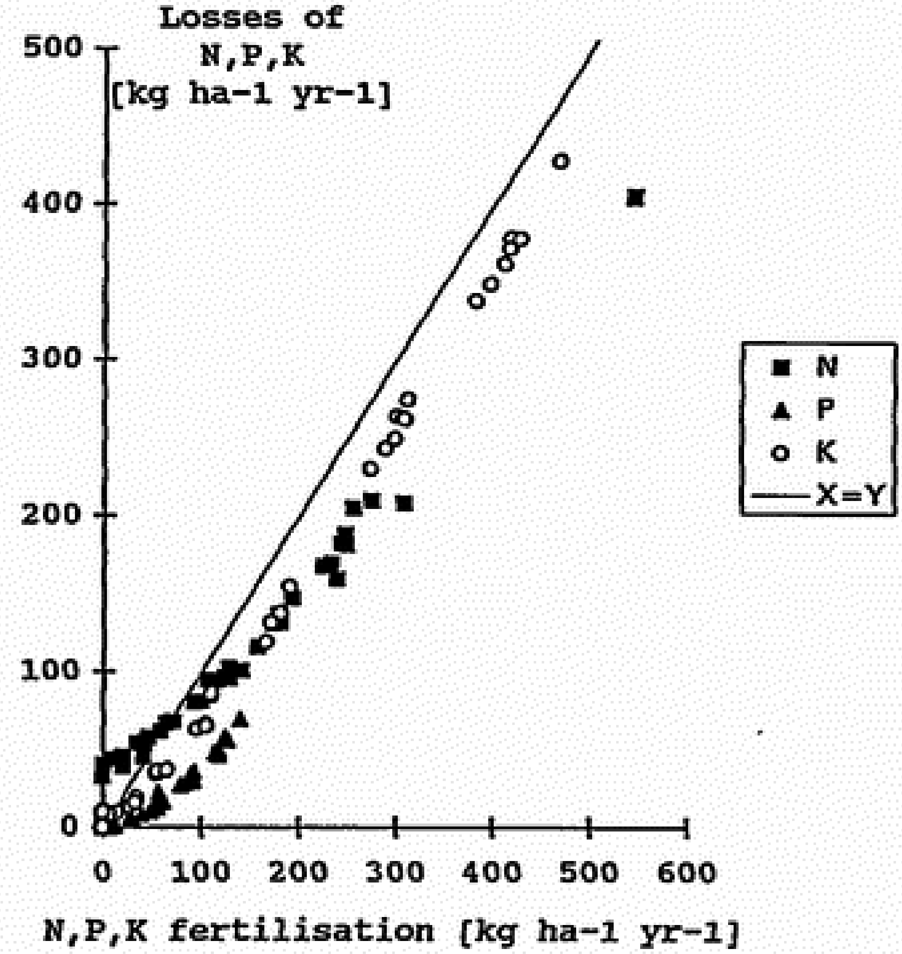


Figure 2. Environmental losses (in kg ha^{-1} year^{-1}) of N, P and K in relation to fertiliser rates (in kg ha^{-1} year^{-1}), for all 122 LUSTs developed for the Neguev settlement.

Table 3. Values of the toxicity parameter for calculation of biocide indices, in relation to the WHO code.

WHO Code	Description	Toxicity parameter
Ia	Extremely hazardous	7
Ib	Highly hazardous	5
II	Moderately hazardous	3
III	Slightly hazardous	1

the same absolute difference in duration is more important at short than at long durations.

WHO codes and durations of toxicity for the various biocides are taken from Martin (1972), Martin & Worthing (1974), Thomson (1981, 1983, 1992, 1993) and Van Schoubroeck *et al.* (1989). The translation of the WHO code into a number is subjective. Indications for the duration of the toxin in the system vary with the method of, and conditions during, determination. Most determinations were under environmental conditions (temperature, soil type, etc.) that are not representative for the Atlantic Zone. Although the values of biocide indices given are therefore tentative, it is assumed that differences in these values reflect the different behaviour of the various biocides also for the Atlantic Zone.

Large differences occur between the biocide indices of the various LUSTs (Figure 3). About 35% of the LUSTs uses no biocides at all, with a resulting biocide index of zero.

3. Quantification of limits to sustainability indicators

Nutrient balances

On the basis of characteristics of the three LUs recognised in the Atlantic Zone (Table 4), indications of amounts of N, P and K in the top 20 cm of each group can be obtained. However, the following should be taken into account:

1) about 40% of the soil organic material is not readily available, due to the formation of complexes with allophanes found, in varying amounts, in all LUs (Veldkamp, 1994)
2) P-Olsen gives only crude estimates of plant available P, and is probably mainly correlated to labile P in the soil (Fixen & Grove, 1990). In the Atlantic Zone, particularly the fertile, well-drained LUs have a high P fixation, and total P available to plants might be higher than indicated by P-Olsen, especially for periods exceeding one cropping season.
3) The fertile LUs are generally very young, showing rapid weathering of primary minerals, liberating 1–10 kg K ha^{-1} $year^{-1}$ (Nieuwenhuyse, 1994), assumed to be independent of the type of land use. For infertile LUs, such weathering is negligible.

For each LU, educated guesses are made to quantify the impact of these considerations and to obtain a reasonable indication of the total amounts of nutrients (Table

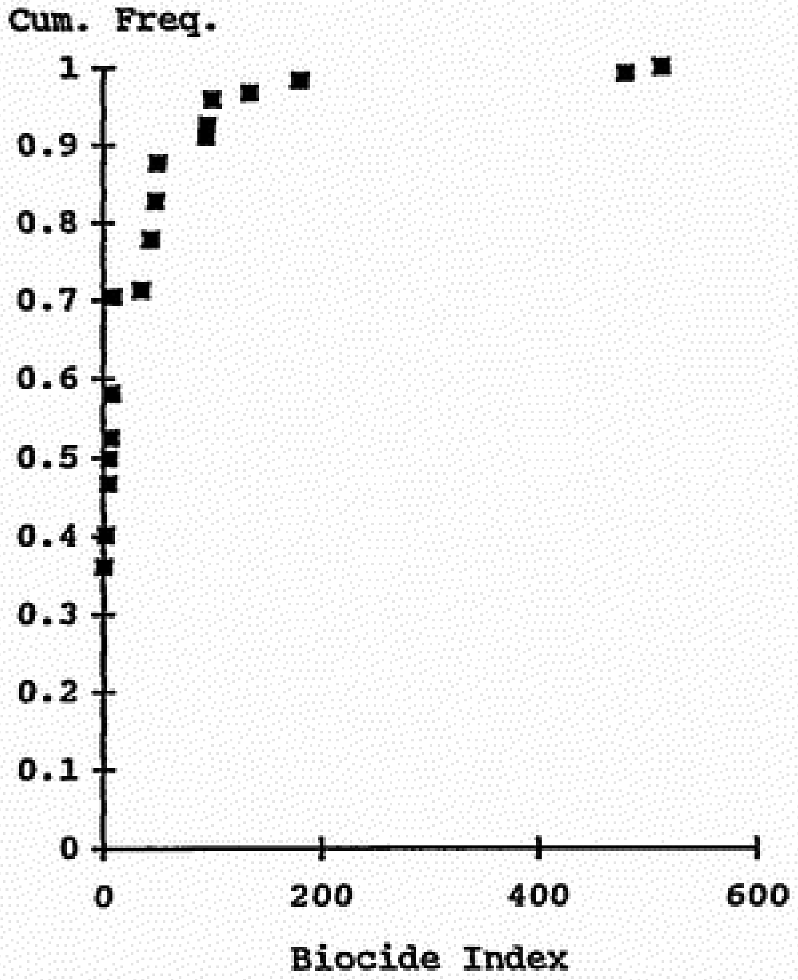


Figure 3. Cumulative frequency distribution of biocide index over all 122 LUSTs developed for the Neguev settlement.

4). On the basis of these totals, limits to yearly losses are calculated, assuming that in the next 10 years the productivity should only be slightly influenced by changes in soil nutrient balance. For each LU, total tolerable loss of N, without a mineral source of supply in the soil, is set at 10% of the total N initially available. For P and K, it is set at 50% for each LU, since P can be liberated from reserves presently bound to soil components and K is released through weathering. Yearly permissible losses are assumed to be constant over the 10 year period (Table 4).

Biocide index

No clear-cut relation exists between the calculated index of biocide use and the sustainability of the system, making calculation of a limit to the biocide index impossible. A value of the limit can only be set subjectively, such as is done by the Dutch Ministry of Agriculture, Nature Conservation and Fishery (LNV), that aims for a 35% reduction of biocide use in 1995 compared to the average over 1984–1988, and a 50% reduction in 2000 (Anonymous, 1990). A similar 50% reduction in biocide use is discussed below.

4. Adaptation of the LP model

Both types of sustainability indicators are incorporated in the constraints of the LP model. These constraints can be activated and expressed at levels higher than that of the LUST:

Table 4. Some characteristics of the top 20 cm of the major LUs in the Atlantic Zone. Observed ranges represent different soils in each group (unpublished data by Nieuwenhuyse). Derived characteristics (see text) are given as single indicative values.

	Land Unit Group		
Soil fertility natural drainage	Fertile Well	Fertile Poor	Infertile Well
Bulk density (g cm^{-3})	0.5 – 0.8	0.8 – 1.1	0.7 – 0.9
Clay (%)	5 – 25	10 – 40	40 – 70
Organic C (%)	3 – 12	1 – 4	3 – 6
P-Olsen (mg l^{-1})	2 – 19	10 – 100	2 – 20
CEC[1] (meq (100 g)$^{-1}$)	20 – 45	20 – 40	15 – 20
Exch. K[2] (meq (100 g)$^{-1}$)	0.2 – 1.5	0.6 – 1.5	0.1 – 0.4
P fixation (%)	75 – 99	25 – 80	40 – 90
pH in H_2O	5.5 – 6.0	6.0 – 7.0	3.9 – 4.5
Correction factor[3]	1.3	2.0	1.3
Total N (kg ha^{-1})	4831	3696	3610
Loss[4] N (kg ha^{-1} year^{-1})	48.3	37.0	36.1
Total P (kg ha^{-1})	299	539	278
Loss[4] P (kg ha^{-1} year^{-1})	15.0	27.0	13.8
Total K (kg ha^{-1})	355	446	297
Loss[4] K (kg ha^{-1} year^{-1})	17.8	22.3	14.8

[1] Soil Cation Exchange Capacity

[2] Soil Exchangeable K

[3] factor to convert mg l^{-1} into mg kg^{-1}; based on comparison between exchangeable Ca and Mg from MAG (meq (100 ml)$^{-1}$) and ISRIC (meq (100 g)$^{-1}$)

[4] total yearly permissible loss

1) Farm type * Land Unit (FT*LU): per area of each land unit for each farm type
2) Farm type total (FTt): total per farm type, irrespective of its size
3) Farm type average per ha (FTa): per farm type, taking farm size into account
4) Land Unit (LU): per total area of each LU in the region
5) Regional (Re): total of the whole region

Which of these levels should be used depends on the type of sustainability indicator, the interest of the user, and the structure of the LP model. The biocide index reflects an effect at the regional level, and a constraint on regional level seems logical. However, a given reduction in biocide use might be achieved by lowering biocide use in only a few of the FTs, without affecting behavior in the others. Also, some FTs might generate too little income, or the spatial distribution of the biocide index might be too skewed. In these cases, inclusion of sustainability constraints at the FTa and/or the LU level may be more appropriate.

The appropriate level to express constraints regarding nutrient balances is at the FT*LU level. Recall that nutrient balances are used to indicate changes in the production potential of the soil. When the LP model calculates optimal land use with more than one LUST on the same LU, it is assumed that these LUSTs are rotated over the total area of that particular LU on the farm. At present, this assumption is made for all LUSTs, but it is realised that it should only hold for LUSTs that have a duration shorter than the time-frame of the analysis. In future versions of the LP model, differences will be made between these LUSTs and longer duration LUSTs. Now, within one FT, different LUSTs on similar LUs can compensate for each others nutrient balances even though no explicit exchange of nutrients is described in the LUSTs. Thus, for example, a leguminous crop with a positive N balance can (partially) compensate for the negative N balance of a maize crop. Due to the fact that LUSTs are described at the field level (Jansen & Schipper, 1995), this type of compensation is not possible for LUSTs that fall on different LUs. Since FTs are assumed to be stable, i.e. not changing in geographic position or size, also no compensation is possible between LUSTs in different FTs. In such cases, exchanges of nutrients are possible only if explicitly formulated in the LUSTs, e.g. the transfer of green manure that is produced on one LU to a crop grown on another, or the feeding of bananas from one FT to cattle on another. The effect of these exchanges on the nutrient balances is thereby accounted for at the LUST level.

5. Description of LUSTs

To enable an analysis of effects on sustainability indicators, LUSTs should be described that differ in the use of factors that influence these sustainability indicators. For the Neguev, LUSTs are described (Jansen & Schipper, 1995) with a wide range in fertiliser and biocide use for cassava, maize, palm-heart, pineapple and plantain. For beef-cattle production systems only a limited range of fertiliser use is described in LUSTs, whereas LUSTs for natural forests and tree plantations only differ in wood extraction methods. Yield and labour use are in concordance with the fertiliser input level, and with the use of fungicides, insecticides and nematicides. Weed removal is either completely manual, or, in other LUSTs, at least partially with chemicals, with the former using more labour but having equal crop yield.

6. Analysis and selection of LUSTs

Rather than the LUSTs themselves, their corresponding technical coefficients are submitted to the LP model. In the present version of MODUS, balances for soil N, P and K, biocide index, monthly labour and land use, and annuities of costs (of all inputs minus labour) and gross income (of all products) are determined for each LUST. Annuities are needed to facilitate comparison of LUSTs with different durations. Ranges can be set for the values of these technical coefficients, to disregard LUSTs with coefficients outside any, or a combination, of these ranges.

7. Running the LP model

In USTED, land use evaluation is performed by comparing results of model runs with different goals, constraints, LUSTs, and/or technical coefficients. In USTED this is called 'comparison of scenarios'. The base scenario is a model run where maximisation of net farm income is the goal-function, while FT specific constraints are set on land and labour availability, but not on sustainability indicators (Schipper *et al.*, 1995). In the various sustainability scenarios, goal and land and labour constraints remain the same, but different sustainability indicators are included in the constraints. No changes are made in LUSTs or in methods to calculate the technical coefficients. In the nutrient balance scenario, permissible losses for soil N, P and K are imposed as constraints at the FT*LU level. Three biocide reduction scenarios are defined differing in the level at which the constraint is set: the 'Regional' scenario sets the total biocide index of the region to maximally 50% of that found in the base scenario, the 'FTt' scenario limits the biocide index for each FT to 50% of that in the base scenario, and in the 'FTa' scenario average biocide index per ha for each FT is maximally 50% of the overall average per ha in the base scenario.

8. Analysis of the results

In this paper, only results of the optimisation model in terms of nutrient balances and biocide indices are discussed. Reference is made to Schipper *et al.*, (1995) for economic and agronomic analysis. In all results, only the well drained LUs were used, hereafter referred to as the fertile and the infertile LU.

In the base-scenario, annual N and K balances are negative, for both LUs and all FTs (Table 5). The annual P balance is slightly negative for the fertile, but positive for the infertile LU, on all FTs. On a per ha basis, only losses of K are higher than is permissible, on all FTs and LUs, except for the fertile LU on FT 2. Thus, K is the most limiting nutrient from a sustainability point of view, at least for the set of LUSTs offered to the LP model. This is confirmed by results of the nutrient balance scenario, where nutrient balances become less negative for both N and K (with the exception for the fertile LU on FT 2), with K at the limit imposed by the constraint. The P balance becomes more positive, due to the fact that in LUSTs with higher fertiliser applications, P is always applied in conjunction with K. A positive P balance not necessarily influences short term crop productivity, since most of this P is fixed by the

Table 5. N, P and K balances in kg ha^{-1} year^{-1} for the Fertile, Well-Drained (FWD) and Infertile, Well-Drained (IWD) LUs at FT*LU and LU level under the base and the nutrient-balance restricted scenarios (see text). The Fertile, Poorly-Drained LU was not used in either scenario.

Scenario		Base			Nutrient balance		
FT	LU	N	P	K	N	P	K
1	FWD	−27.0	−0.6	−22.9	−21.6	−0.5	−17.8
	IWD	−21.0	12.0	−18.1	−17.5	15.9	−14.8
2	FWD	−6.8	0	−6.2	−20.5	−0.3	−17.8
	IWD	−24.1	0.5	−16.5	−22.5	1.9	−14.8
3	FWD	−27.0	−0.6	−21.9	−21.7	−0.5	−17.8
	IWD	−22.3	7.2	−17.4	−19.4	10.5	−14.8
4	FWD	−25.7	−0.6	−20.9	−21.5	−0.5	−17.8
	IWD	−17.0	26.6	−20.1	−10.1	36.4	−14.8
5	FWD	−27.0	−0.6	−21.9	−21.6	−0.5	−17.8
	IWD	−23.1	4.0	−17.0	−20.9	6.3	−14.8
Tot[1]	FWD	−26.0	−0.6	−21.1	−21.6	−0.5	−17.8
	IWD	−22.9	4.8	−17.1	−20.6	7.3	−14.8

[1] Total for the whole Neguev area.

soil. However, to take account of the longer term effect of the accumulation of P, alternative LUSTs should be developed, with a lower P fertilisation, and similar or higher N and K applications compared to the LUSTs currently used. Alternatively, a constraint can be set on the maximum rate of P accumulation.

In the regional biocide scenario, reduction of the biocide index is achieved by adjusting only the cropping system of FT 5 (Table 6). On this FT, changes in use of the infertile LU contribute to almost all the reduction in the biocide index. Although this may be optimal in terms of biocide reduction and income generation at the regional level, it results in a lower income for FT 5 whereas incomes for other FTs remain constant (Schipper *et al.*, 1995). In the FTt scenario, farm size is not taken into account, and average biocide use per ha is not considered, but only the total over all the land of the farm. This means that also on FT 1 the biocide index has to be reduced with 50%, even though in the base scenario it already has a per ha biocide index of less than 50% of the average. In the FTa scenario, all FTs achieve the same average index per ha over the total area per FT, except for FT 1 which maintains its low bio-

Table 6. Total biocide index and average per ha, at FT*LU, FT, LU and regional level for the Fertile, Well-Drained (FWD) and Infertile, Well-Drained (IWD) LUs in the base and the biocide restricted scenarios (see text). The Fertile Poorly-Drained LU was not used in either scenario. Areas in use per LU vary slightly (<0.2 ha) between scenarios (not indicated).

Scenario		Base		Region		FTt		FTa	
FT	LU	tot	av	tot	av	tot	av	tot	av
1	FWD	1993	32	1993	32	1916	31	1993	32
	IWD	5194	36	5194	36	1677	12	5194	36
	TOTAL	7187	14	7186	14	3593	7	7186	14
2	FWD	150	11	259	19	259	19	259	19
	IWD	3700	37	3705	37	1666	17	1666	17
	TOTAL	3850	30	3963	31	1925	15	1924	15
3	FWD	9635	30	635	30	7446	23	7633	24
	IWD	8641	34	8641	34	1692	7	1692	7
	TOTAL	18277	29	18277	29	9138	15	9326	15
4	FWD	16627	37	16498	37	8116	18	6666	15
	IWD	1058	4	1060	4	727	2	727	2
	TOTAL	17685	36	17558	36	8843	18	7393	15
5	FWD	2908	20	2908	20	2908	20	2908	20
	IWD	76977	35	13549	6	37034	17	34120	16
	TOTAL	79885	32	16457	7	39943	16	37028	15
Tot[1]	FWD	31314	32	31293	32	20646	21	19459	20
	IWD	95571	35	32149	12	42796	16	43399	16
	TOTAL	126884	30	63442	15	63442	15	62857	15

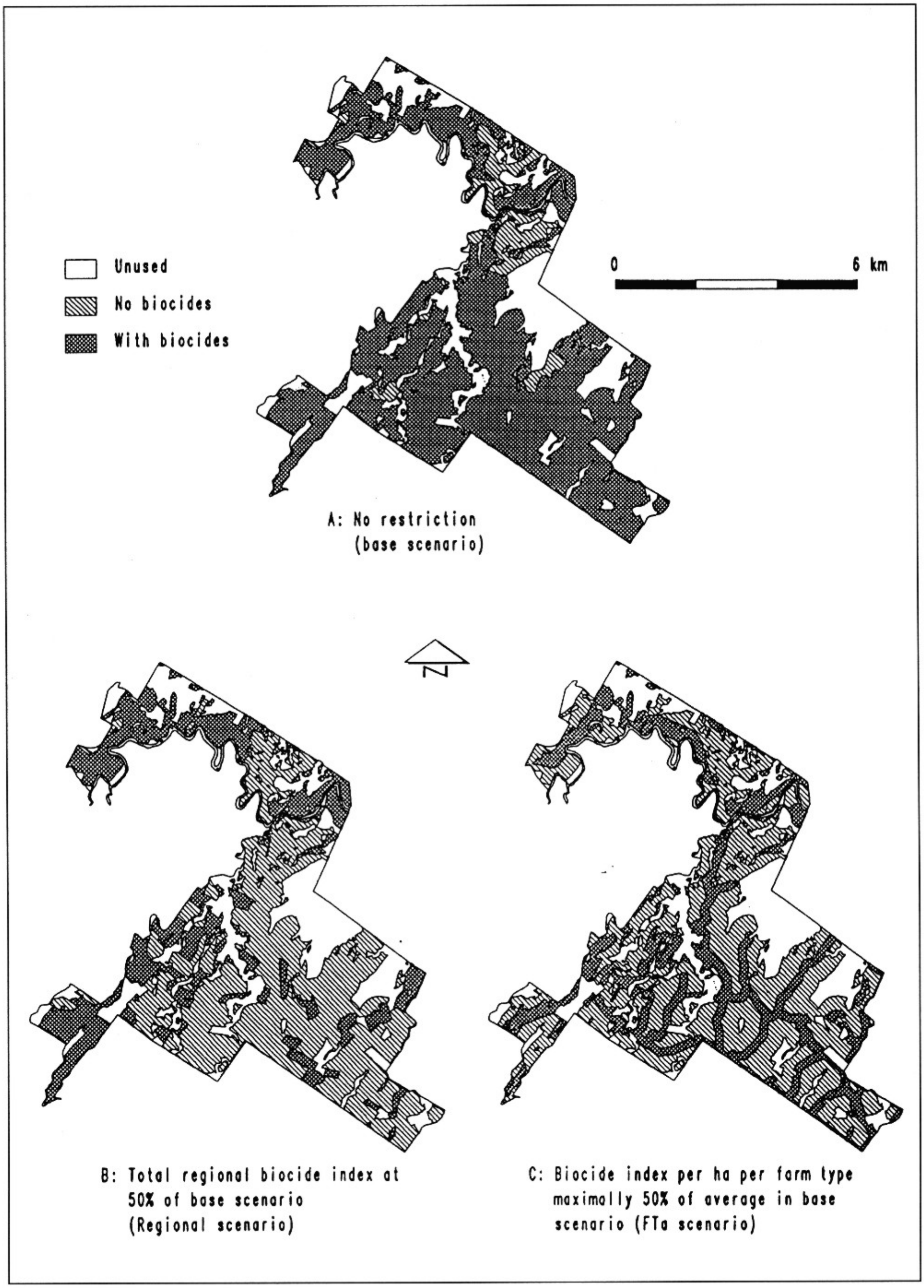
[1] Total of the whole Neguev area.

cide use. The resulting reduction in the biocide index at the regional level thus even exceeds 50%.

The spatial distribution of land use is not important for the nutrient balance as an indicator of the sustainability of the soil productivity. By imposing constraints at the FT*LU level, the LP model limits the loss of nutrients at each LU per FT. For indicating off-site effects of biocide use, however, the calculations by the LP model are not sufficient, since the model does not consider spatial distribution of land use. The GIS is used to link the LP results to the location of the farm types, to enable analysis of the spatial distribution of biocide use. In the base scenario, LUSTs with biocides (indices of 43 and 50) are found evenly distributed over the Neguev (Figure 4a), and in fact only the areas furthest from roads have other LUSTs or, like the poorly-drained soils, they are not used. In the scenario that reduces the biocide index at the regional level, use of biocides is more strongly concentrated in the areas close to rivers where the fertile soils are located (Figure 4b). Again a more evenly distributed biocide use is achieved in the FTa (Figure 4c) and FTt scenarios (results not shown, but very similar to FTa), where in fact biocide use is strongly related to proximity of the roads. This is due to the assumption that LUSTs with higher labour input are found closer to a road (Stoorvogel, 1995), while higher labour use concurs with higher biocide use. If dilution of biocide use is to be preferred, the FTa and FTt scenarios are superior to the regional scenario.

Discussion and conclusions

In USTED, the LUSTs submitted to the LP model, are not necessarily sustainable by construction. This is in contrast to the approaches of Veeneklaas *et al.* (1990) and Kruseman *et al.* (1995), who claim to use only sustainable options for land use in their analyses, while sustainability is defined in terms of nutrient balances. Criteria to indicate the sustainability of land use can be incorporated at various levels in the USTED system: LUST, Farm Type (total and averaged per ha), Land Unit, Farm Type * Land Unit, and Region. If interactions occur between alternative forms of land use (such as at the LUST level where, on the same LU and for the same FT, LUSTs with a higher fertiliser input can compensate those with a lower fertiliser input), care should be taken to select the proper level at which sustainability criteria are used as constraints in the LP model. This allows for the selection of non-sustainable LUSTs by the LP model, while still achieving a sustainable land use at higher levels. Therefore, submitting only sustainable LUSTs to the LP model only unnecessarily restricts the analysis of land use to a limited set of options. However, limiting the number of LUSTs may be needed for pragmatic reasons, such as the limited capacity of the LP software. An ex-ante evaluation and selection of LUSTs can be done to analyse the performance of LUSTs in terms of all, or a selection of, the objective and constraints in the LP model. It should be realised however, that such a selection is subjective, as is the resulting omission of LUSTs.



A: No restriction (base scenario)

B: Total regional biocide index at 50% of base scenario (Regional scenario)

C: Biocide index per ha per farm type maximally 50% of average in base scenario (FTa scenario)

Figure 4. Land use with biocides (indices 43 and 50; indicated in black) in the Neguev settlement in three scenarios with different limitations to the maximum biocide index (see text).

In recent studies (Ehui & Spencer, 1993; Solórzano *et al.*, 1991), the costs of negative nutrient balances are calculated as the cost of the amount of fertiliser that contains the equivalent to the amount of nutrients lost. This approach does not account for the fact that simply supplying this amount of fertiliser does not restore the nutrient content of the soil to the original state, since losses for example due to leaching, always occur. Also, it does not consider that often a higher investment in fertilisers is accompanied by investments in protective measures (weeding, biocide applications, irrigation). Additionally, it does not recognise the fact that other forms of reducing loss of nutrients exist, e.g. by growing other crops, or accepting lower production levels.

Costs for improving the sustainability of land use can vary by LUT and LU. This is taken into account in the description of the specific input/output relations in the various LUSTs, which indeed differ among LUTs and LUs. In USTED, the cost of pursuing more sustainable production systems can be calculated as the difference between the net income generated in the base scenario, without sustainability constraints, and that in scenarios which include such constraints. This method is more accurate than the indication of replacement costs for single factors.

In the examples given, changes in sustainability of land use were studied by imposing constraints in the LP model on the values of the sustainability indicators, while maximising net farm income. Alternatively, minimisation of one of these indicators can be made into the goal-function, while setting a minimum to farm income. In doing so, the farm as decision making level is replaced by a higher level.

The inclusion of GIS in the USTED methodology, enables an analysis of the spatial aspects of land use. In certain situations, such an analysis can reveal that the optimal land use as calculated by the LP model is less sustainable than expected, e.g. due to geographic concentration of waste production.

The method of LP limits the number and types of sustainability indicators that can be included in the methodology. The choice as to which indicators to include in the analysis is often guided by (lack of) information, and as such it is subjective. This should be reflected in the period for which the outcome of the analysis is claimed to be valid.

Acknowledgements

The working group Costa Rica (WAU) facilitated the work underlying this publication. Thanks are especially due to Johan Bouma, Louise Fresco and Salle Kroonenberg. Hans Jansen (AZP) is kindly acknowledged for comments on earlier drafts, and for indicating some interesting references. Many thanks to Andre Nieuwenhuyse (AZP) for sharing his great knowledge of the Atlantic Zone in general and of its soils in particular, and for helping to improve an earlier manuscript. Much of the data underlying the presented work is in unpublished MSc theses by students of WAU:

Steve Chin, Leendert den Daas, Cees Epker, Olaf Erenstein, Raymond Jongschaap, Jörg Tönjes, Harry Leummens, Stephan Mantel, Ted de Jong, GertJan Weerts and Sandra de Wolff. Also Antje Weitz (formerly AZP) and Rein Poels (WAU) contributed with unpublished data. Thanks are due to all of them. Two anonymous reviewers are acknowledged for their comments.

References

Angus, J.F., J.W. Bowden & B.A. Keating, 1993. Modelling nutrient responses in the field. *Plant and Soil* 155/156: 57–66.

Anonymous, 1990. Multi-year plan for crop protection: policy intentions. (In Dutch) Ministerie van Landbouw, Natuurbeheer en Visserij,.The Hague, 273 pp.

Anonymous, 1993. FESLM: an international framework for evaluating sustainable land management. World Resources Report 73. Land and Water Development Division, FAO, Rome, 74 pp.

Anonymous, 1994. Sustainable risks: a permanent reality (In Dutch). Wetenschappelijke Raad voor het Regeringsbeleid. Rapporten aan de regering 44. SDU Uitgeverij, Den Haag, 208 pp.

Berentsen, P.B.M. & G.W.J. Giesen, 1994. Economic and environmental consequences of different government policies to reduce N losses on dairy farms. *Netherlands Journal of Agricultural Science* 42: 11–19.

Castillo, L.E., C. Ruepert & E. Solis, 1993. Pesticide residues in aquatic ecosystems of lowland areas in Costa Rica. Poster presented at the 4th workshop on modern pesticides, Prague.

De Bruin, S., 1992. Estudio detallado de los suelos del asentamiento Neguev. Working document No. 25, Atlantic Zone Programme, CATIE, Turrialba, 39 pp. + App.

De Camino, R. & S. Müller, 1993. Sostenibilidad de la agricultura y los recursos naturales: Bases para establecer indicaciones. IICA Programa II. Serie documentos de programas 38. IICA, San José, 134 pp.

De Koning, G.H.J., H. Janssen & H. Van Keulen, 1992. Input and output coefficients of various cropping and livestock systems in the European Communities. Wetenschappelijke Raad voor het Regeringsbeleid. Working Document W62, The Hague, 71 pp.

Dent, J.B., 1993. Potential for simulation in farming systems research? In: F.W.T. Penning de Vries, P. Teng & K. Metselaar (Eds.), Systems approaches for agricultural development. Kluwer, Dordrecht, pp. 325–339.

Dercksen, P., 1991. A soil erosion mapping exercise in Costa Rica: Purposes, methodology and results. In: W.G. Vahrson, M. Alfaro & G. Palacios, Taller de erosión de suelos, memoria. Universidad Nacional, Heredia, pp. 164–170.

Ehui S.K. & D.S.C. Spencer, 1993. Measuring the sustainability and economic viability of tropical farming systems: a model from sub-Saharan Africa. *Agricultural Economics* 9: 279–296.

Fixen, P.E. & J.H. Grove, 1990. Testing soils for Phosphorus. In: R.L. Westerman (Ed.), Soil testing and plant analysis. Third Edition. Soil Science Society of America Inc., Madison, Wisconsin, pp. 141–180.

Fresco, L.O. & S.B. Kroonenberg, 1992. Time and spatial scales in ecological sustainability. *Land Use Policy* 9: 155–168.

Hazell, P.B.R & R.D. Norton, 1986. Mathematical programming for economic analysis in agriculture. Macmillan Publishing Company, New York, 400 pp.

Ibrahim, M.A., 1994. Compatibility, persistence and productivity of grass-legume mixtures for sustainable animal production in the Atlantic Zone of Costa Rica. PhD thesis, Agricultural University Wageningen, 129 pp.

Jansen, D.M. & R.A. Schipper, 1995. A static, descriptive approach to quantify land use systems. *Netherlands Journal of Agricultural Science*: this issue.

Jury, W.A. & H. Flühler, 1992. Transport of chemicals through soil: mechanisms, models, and field applications. *Advances in Agronomy* 47: 141–201.

Kruseman, G., R. Ruben, H. Hengsdijk & M.K. Van Ittersum, 1995. Farmhousehold modelling for estimating the effectiveness of price instruments in land use policy. *Netherlands Journal of Agricultural Science*: this issue.

Lélé, S.M., 1991. Sustainable development: a critical review. *World Development* 19: 607–621.

Martin, H. (Ed.), 1972. Insecticide and fungicide handbook for crop protection. 4th Ed. Blackwell Scientific Publications, Oxford, 415 pp.

Martin, H. & C.R. Worthing (Eds.), 1974. Pesticide manual. 4th Ed. British Crop Protection Council, 565 pp.

Montero, S.C., E. Malavassi, F. Güendel, V. Conzález, E. Fernández, F. De Obaldía, D. Rojas, H. Rodríguez, A. Mata, R. Van Der Laat, V. Balboza & T. Marino, 1991. Informe preliminar Terremoto 22 de abril de 1991, Ms: 7.4 Valle de la Estrella, Limón, Costa Rica. OVSICORI-UNA, Heredia, 22 pp.

Monturiol, S., 1994. Contaminación alcanza las profundidades de la tierra. *UNA informa*, June: 5.

Nieuwenhuyse, A., 1994. Quantitative aspects of weathering and neoformation in volcanic soils in perhumid tropical Costa Rica. Transactions 15th World Congress of Soil Science, Acapulco, Vol. 8a, pp. 116–129.

Niu, W.Y., J.J. Lu & A.A. Khan, 1993. Spatial systems approach to sustainable development: A conceptual framework. *Environmental Management* 17: 179–186.

Pearce, D.W. & R.K. Turner, 1990. Economics of natural resources and the environment. Harvester Wheatsheaf, New York, 378 pp.

Rabbinge, R. & H.C. Van Latesteijn, 1992. Long-term options for land use in the European community. *Agricultural Systems* 40: 195–210.

Rosales, A., P. Maebe & R. Sevenhuysen, 1994. Determination of losses of nutrients and nematicides on a banana plantation in the Atlantic Zone. Internal report 33 Phase 2 Atlantic Zone Programme, CATIE/MAG/AUW, Turrialba, 32 pp.

Sader, S.A. & A.T. Joyce, 1988. Deforestation rates and trends in Costa Rica, 1940–1983. *Biotropica* 20: 11–10.

Schipper, R.A., D.M. Jansen & J.J. Stoorvogel, 1995. Sub-regional linear programming models in land use analysis: a case study of the Neguev settlement, Costa Rica. *Netherlands Journal of Agricultural Science*: this issue.

Selim, H.M., 1992. Modelling the transport and retention of inorganics in soils. *Advances in Agronomy* 47: 331:384

Solórzano, R., R. De Camino, R. Woodward, J. Tosi, V. Watson, A. Vásquez, Carlos Villalobos, J. Jiménez, R. Repetto & W. Cruz, 1991. Accounts overdue: Natural resource depreciation in Costa Rica. Tropical Science Center, San José, World Resources Institute, Washington DC, 110 pp.

Spaans, E.J.A., G.A.M. Baltissen, J. Bouma, R. Miedema, A.L.E. Lansu, D. Schoonderbeek & W.G. Wielemaker, 1989. Changes in physical properties of young and old volcanic soils in Costa Rica after clearing of tropical rain forest. *Hydrological Processes* 3: 383–392.

Spharim, I., R. Spharim & C.T. De Wit, 1992. Modelling agricultural development strategy. In: Th. Alberda, H. Van Keulen, N.G. Seligman & C.T. De Wit (Eds.), Food from dry lands. Kluwer Academic Publishers, Dordrecht, pp. 159–192.

Stoorvogel, J.J., 1993. Optimizing land use distribution to minimize nutrient depletion: a case study for the Atlantic Zone of Costa Rica. *Geoderma* 60: 277–292.

Stoorvogel, J.J., 1995. Linking GIS and models: structures and operationalisation for a Costa Rican case study. *Netherlands Journal of Agricultural Science*: this issue.

Stoorvogel, J.J., R.A. Schipper & D.M. Jansen, 1995. USTED: a methodology for a quantitative analysis of land use scenarios. *Netherlands Journal of Agricultural Science*: this issue.

Thomson, W.T., 1981. Agricultural chemicals. Book II Herbicides. 1981–1982 revision. Thomson Publications, Fresno, USA. 274 pp.

Thomson, W.T., 1983. Agricultural chemicals. Book III Fumigants, Growth regulators, Repellents, and Rodenticides. 1983–1984 revision. Thomson Publications, Fresno, 183 pp.

Thomson, W.T., 1992. Agricultural chemicals. Book I Insecticides. 1992 revision. Thomson Publications, Fresno, 302 pp.

Thomson, W.T., 1993. Agricultural chemicals. Book IV Fungicides. 1993–1994 revision. Thomson Publications, Fresno, 226 pp.

Van Schoubroeck, F.H.J., M. Herens, W. De Louw, J.M. Louwen, T. Overtoom, 1989. Managing pests

and pesticides in small scale agriculture. CON/CTA/TOOL, Wageningen, 204 pp.
Veeneklaas, F.R., S. Cissé, P.A. Gosseye, N. Van Duivenbooden & H. Van Keulen, 1990. Compétition pour des ressources limitées: le cas de la cinquième région du Mali. Rapport 4: Scenarios de développement. CABO, Wageningen and ESPR, Mopti, 182 pp.
Veldkamp, E., 1994. Organic carbon turnover in three tropical soils under pasture after deforestation. *Soil Science Society of America Journal* 58: 175–180.