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Uncertainties in input-output coefficients for land use optimization studies: an illustration with fertilizer use efficiency

J. BESSEMBINDER

Department of Agronomy, Wageningen Agricultural University, Haarweg 333, NL-6709 RZ Wageningen, The Netherlands

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Abstract

Explorative land use optimization studies using linear programming require input-output coefficients of agricultural land use, which are based on insight in the processes involved. However, insight in these processes is not always sufficient, and often information on quantification of known processes is too limited to describe adequately all production technologies in the soil and climate combinations that prevail in the region. This results in uncertainties in many coefficients, which might greatly affect the results and conclusions of the study. The current paper focusses on the problem of these uncertainties in input-output coefficients, using the uncertainty in estimating the fertilizer use efficiency as an illustration. An example of uncertainty due to lack of knowledge on processes involved is the use of different approaches for estimating fertilizer use efficiency in two land use optimization studies. A further problem is uncertainty due to lack of data, this is illustrated with an example from the Atlantic Zone of Costa Rica. Very few data are available to determine fertilizer use efficiency and data from regions with similar soil and climate type are not available either. Data from non-similar regions may not give the right impression of the possibilities in the region.

Different concepts and sources of information result in different estimates of coefficients, which might in turn greatly influence the results of the linear programming model. It is therefore concluded that, rather than using one fixed value for a particular input-output coefficient, the effect of uncertainty in coefficients on the final results of the model should be examined.

Keywords: uncertainty, linear programming, land use optimization, fertilizer use efficiency

Introduction

The project 'Agro-ecological analysis of regional scenarios', part of the programme 'A methodology for analysis and planning of sustainable land use, a case study in Costa Rica' aims at exploring the possibilities for future land use in a region with the help of a Multiple Goal Linear Programming (MGLP) model. Special attention is given to the consequences of uncertainties in estimates of model input-output coefficients.

Since the eighties, the Linear Programming (LP) technique has been used in land use optimization studies. We distinguish two categories: predictive studies and explorative studies. Both types of studies can be complementary, but differ essentially in their approach and objectives. Predictive studies aim mostly at forecasting developments in land use in the short term and have a strong socio-economic component. Descriptions of production technologies are often based predominantly on current farming practices (Anonymous, 1981; Sharifi, 1992; Erenstein & Schipper, 1993). Explorative studies, on the other hand, explore the possibilities for sustainable land use in the long term. Because of ever changing socio-economic factors, these studies use the more or less stable bio-physical limits. Descriptions of production technologies are based on insight in underlying bio-physical processes, which enables the definition of new, technically efficient ways of production, not yet practised (Veeneklaas *et al.*, 1991; Rabbinge *et al.*, 1994; Stroosnijder *et al.*, 1994).

For the explorative studies, addressed in this paper, multiple data on inputs and outputs of production systems and objectives of different interest groups are needed. In hardly any land use optimization study sufficient information is available to cover the whole range of technically efficient ways of production for all soil and climate combinations prevailing in the field. Therefore, estimation of input-output coefficients for LP-models involves many uncertainties.

Uncertainty is related to lack of knowledge, however, the character of the lack of knowledge is not always the same. Uncertainty may be due to:

1. lack of knowledge of processes involved;
2. lack of data for quantification of processes;
3. spatial and temporal variation (e.g. in weather, soils, prices).

If underlying processes are investigated, uncertainties of the first category may transform into uncertainties of the second category. If also sufficient data are collected for quantification, these uncertainties disappear or transform into uncertainties of the third category. Sometimes stochastic variables are introduced to describe this third type of uncertainty (Hendrix, 1989). In recent explorative land use optimization studies (Veeneklaas *et al.*, 1991; Rabbinge *et al.*, 1994) some sensitivity analyses were carried out to analyse the effect of uncertainties, but mainly concerning variation in economic variables like prices and costs, and hardly concerning uncertainty in input-output coefficients of production technologies due to insufficient knowledge on processes or lack of data for their quantification.

The aim of this paper is to draw attention to the first two types of uncertainties. Particularly these types of uncertainties have escaped notice in most LP-models, or if information on these uncertainties was available it was hardly ever used in a post-optimality analysis. These uncertainties can influence the final scenarios and, therefore, the conclusions. An illustration of both types of uncertainty is given in the first two sections with the help of Fertilizer Use Efficiency (FUE). FUE is defined here as the yield at a certain fertilizer application rate minus the yield at zero application, divided by the fertilizer application rate. This coefficient plays a crucial role in the quantification of one of the most important inputs, i.e. fertilizer. FUE is analyzed by considering two aspects: crop nutrient concentrations and apparent fertilizer recovery (Figure 1). In the final section a possible way of handling the uncertainties due to lack of knowledge on processes involved or due to lack of data for

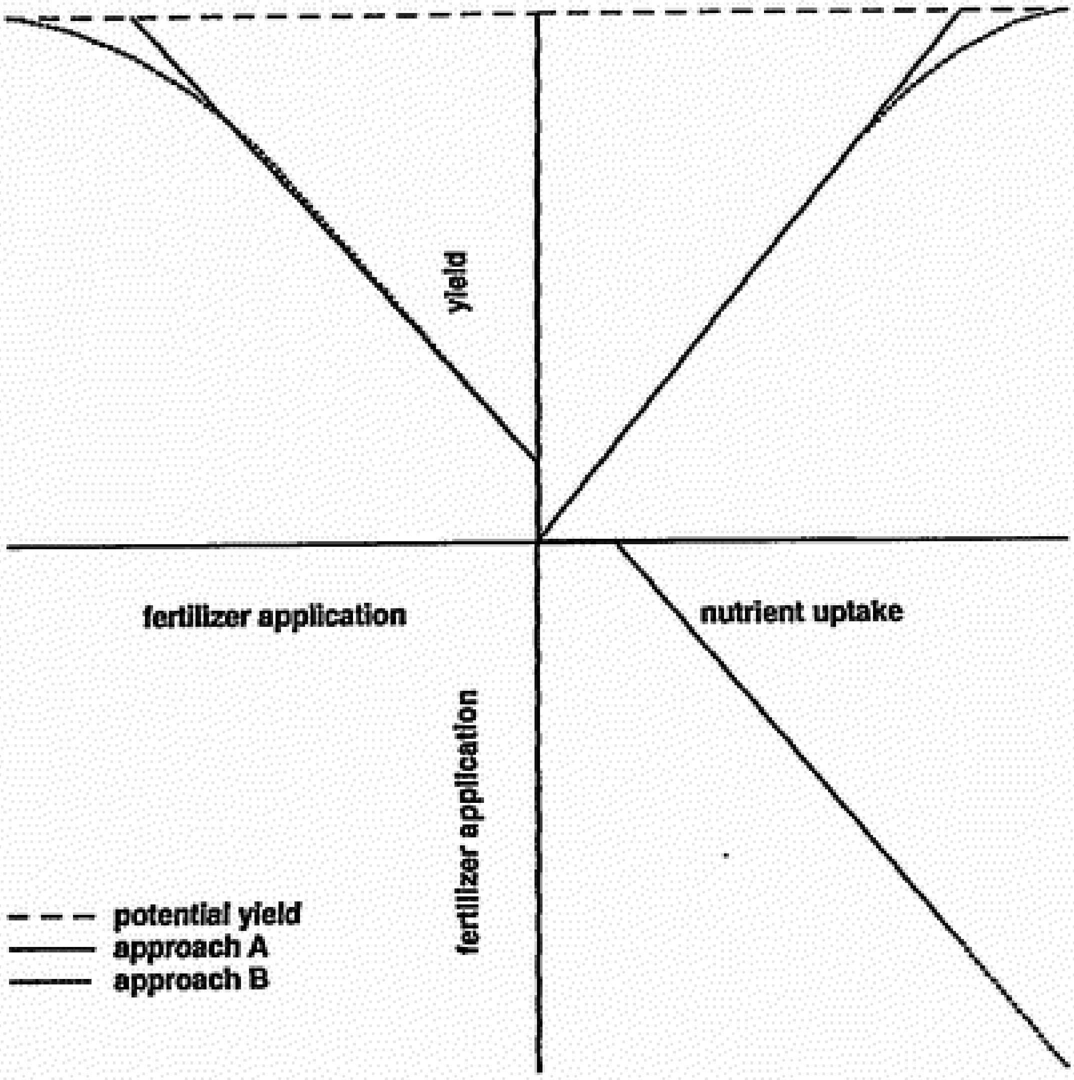

Figure 1. Relation between yield, nutrient uptake, and nutrient application. The slope of the lines in quadrant 1 represents the nutrient concentration, the slope in quadrant 2 is the apparent fertilizer recovery and the slopes in quadrant 3 represent the fertilizer use efficiency. Approach A: the study on the rural areas of the European Community (De Koning *et al.*, 1992). Approach B: the study on the fifth region of Mali (Van Duivenbooden, 1992).

quantification is discussed. Future research will focus on analyzing the effects of uncertainty in LP-models.

Uncertainty due to lack of knowledge of processes involved

While studying various land use optimization studies, it was observed that sometimes different methods were used to estimate the same type of coefficients, thus revealing a lack of knowledge on the processes involved. In this section uncertainty due to lack of knowledge is illustrated with the description of the approaches to estimate the nutrient concentrations and the apparent fertilizer recovery, used in two explorative studies. The methods are discussed afterwards.

The fifth region of Mali

For the study on the fifth region of Mali (Veeneklaas *et al.*, 1991) a review of nutrient concentrations and fertilizer recoveries in rainfed grain crops, leguminous crops, cotton, and irrigated rice in the study area and in regions with similar soils and climate was made by Van Duivenbooden (1992). The review showed that crop nutrient concentrations in systems with high production levels (for maize > 4–5 $ton.ha^{-1}$) were on average 1.4 times higher for grain and 1.7 times higher for straw than the minimum concentrations found. For systems with relatively low production levels these factors were on average 1.2 for grain and 1.3 for straw. In the LP-model the factors 1.4 and 1.7 were used to estimate the crop N, P and K concentrations in intensive systems, defined in the study as systems with a production level equal to 80% of the simulated water-limited production (limited by temperature, radiation and water only). For semi-intensive systems, defined as systems with a production level equal to 32% of the water-limited production, and for extensive systems with actual production levels, the factors 1.2 and 1.3 were used for grain and straw, respectively. The researchers considered it unlikely that lower nutrient concentrations would be obtained, because practically never an optimum balance between all production factors at every moment will be obtained due to heterogeneity in the field and unpredictability of the weather (Van Keulen, pers. comm.).

Apparent fertilizer recoveries were calculated by linear regression between fertilizer application and total nutrient uptake as measured at harvest. Recovery fractions of N, P and K were assessed for each soil type (combination of texture class and soil fertility) under rainfed and irrigated conditions. Precipitation deficit was not taken into account, because too few data were available to establish a relationship. No distinction was made between rainfed crops, because observed fertilizer recoveries were almost similar (averages: 0.36–0.39 for nitrogen; 0.12–0.16 for phosphorus; 0.34–0.38 for potassium). Compared to world-wide average values, relatively low apparent fertilizer recoveries were assumed (Table 6), but most data have been obtained under researcher-managed conditions and it was assumed that in farmer fields these high recoveries can not be obtained (Van Duivenbooden, 1992). Still, the assumed recoveries are relatively high compared to the actual recoveries obtained in the region. As a result of constant apparent fertilizer recoveries and increasing nutrient concentrations, diminishing FUEs were used with increasing yield levels (Figure 1).

The rural areas of the European Community

In the study 'Ground for choices: four perspectives for the rural areas of the European Community' (Rabbinge *et al.*, 1994), most attention has been devoted to N. In the LP-model average crop N-concentrations were taken for all production levels, ranging from potential production, limited by temperature and radiation only, to 80% of the water-limited production. The average concentrations were based on literature from all over the world. The concentrations in the marketable product and the residues of the plant were assumed to be crop-specific constants, high enough to allow for non-constrained production (De Koning *et al.*, 1992).

Apparent recoveries of chemical fertilizer N were derived from literature. At potential production, soil water status is optimal for N-uptake. For water-limited production often lower fertilizer recoveries were assumed, because uptake of N is hampered under sub-optimal water availability. The influence of soil type and climate on recovery was included. In many cases insufficient information was available on the influence of these factors. Therefore, general rules had to be applied based on expert knowledge. For each crop, a range of fertilizer recovery fractions was defined as a function of precipitation deficit and soil texture, based on expert knowledge and taking into account unavoidable inefficiencies, e.g. due to heterogeneity in the field, but assuming optimum management, i.e. best technical means[1] (De Koning *et al.*, 1992). The former implies that fertilizer recovery is not directly related to yield level, only indirectly via the water availability. As a result of these fertilizer recoveries and constant nutrient concentrations, the FUE did not decrease with increasing yield levels (Figure 1).

Observations on the approaches to estimate nutrient concentrations and apparent fertilizer recoveries

The approach to estimate nutrient concentrations, used in the study on the rural areas of the European Community is based on the theory of De Wit (1992), who argued that: 'with some reservations regarding the control of pests, diseases and weeds, it may be concluded that no production resource is used any less efficiently and most production resources are used more efficiently, with increasing yield level due to the further optimizing of growing conditions'. This approach supposes that most production factors can be used simultaneously in the most efficient way. In other words, a high efficiency of one production factor does not diminish the possibility to reach a high efficiency for other production factors. The level of technical efficiency depends on the management and the production situation, i.e. the physical circumstances prevailing in the field. However, in all experiments, including the ones shown by De Wit (1992), nutrient concentrations increase as production approaches the potential level. Until now, little information is available on the interaction of production factors, especially at high production levels. Therefore, it is not known if indeed most production factors, including nutrients, can be used in the most efficient way simultaneously or that efficiency will diminish at the highest yield levels. As a result, in the study on the rural areas of the European Community, where average concentrations were used, especially at the lower production levels nutrient concentrations may have been overestimated. In the study on the fifth region of Mali especially at the higher production levels nutrient concentrations may have been overestimated.

Van Keulen & Van Heemst (1982) showed that the relation between nutrient application and nutrient uptake is generally linear for N and K over the full range of applications up to maximum uptake. The same authors mention that for P this linearity does not hold in general, because the reactions of phosphates in the soil solution and

[1] Best technical means: 'Available knowledge and available means of production are optimally applied, which precludes any waste or inefficient use of resources. Current economic conditions, nor farm infrastructure present constraints to farming practices' (De Koning *et al.*, 1992; p. 3)

the solid phase of the soil are not of simple first order kinetics. However, in both studies mentioned earlier, constant apparent fertilizer recoveries were used for all nutrients. In the study on the fifth region of Mali, where P is taken into account, this may cause underestimation or overestimation of P-recovery. In the same study no distinction was made between the different rainfed crops. Often differences between crops in apparent fertilizer recovery, especially for P, are related to differences in root distribution (De Willigen & Van Noordwijk, 1989). However, in the fifth region of Mali only minor differences in fertilizer recoveries were found between the crops included in the LP-model, so it was decided to take the same fertilizer recovery fractions for all rainfed crops.

The choice between an approach with constant crop nutrient concentrations and an approach with increasing concentrations with increasing yield levels, is not easily made due to a lack of knowledge of underlying processes. In both studies a constant apparent fertilizer recovery was used. However, also here uncertainty due to a lack of knowledge exists, e.g. for P this constant apparent fertilizer recovery does not hold in general.

Uncertainty due to lack of data for quantification of processes

Ideally, data from the region itself are used for the quantification of production technologies in land use optimization studies. If data from the region are insufficiently available, data from literature, preferably from similar regions, theoretical rules or expert judgement will have to be used. In this section an illustration of lack of data from the region itself is given with data on FUE in maize in the Atlantic Zone of Costa Rica. For this crop most data are available. After a description of the available data and a re-analysis, the available data are discussed and compared with data from other information sources.

Available data in the Atlantic Zone of Costa Rica

In the Atlantic Zone of Costa Rica with a hot and humid climate (average annual temperature ± 25 °C, 4000–7000 mm annual rainfall with a monthly precipitation surplus) and soils mainly from volcanic origin, agricultural research on maize has focused especially on screening new varieties and suitable management techniques for the region (Avila Vega, 1984; Calderon, 1984; Ceballos, 1979; Diaz Diaz, 1975; Foster Russell, 1982; Gomez, 1988). In most experiments data on nutrient concentrations or uptake of several plant parts were missing. For maize only two data sets with the needed information were available.

The first data set (Data set 1; Erenstein, 1989) was collected in 1987 at 34 farms on 6 soil types (Table 1). Six incomplete records were left out. The fields were managed by farmers and mostly local varieties were used. Planting density varied from 18.000 to 70.000 plants.ha^{-1}. The rate of fertilizer application reported by farmers varied widely: 12–140 kg N.ha^{-1}, 0–21 kg P.ha^{-1} and 0–20 kg K.ha^{-1}. Weeds were generally controlled with herbicides. The fields were harvested 3-5.5 months after sowing and samples were taken in subplots. The second data set (Data set 2; Chin-

Table 1. Some soil data from Data set 1 and 2, for unfertilized soils (standard deviation between brackets).

	Data set 1[a]	Data set 2[b]	
		fertile soil	infertile soil
pH(H_2O)	5.8 (0.4)	6.1 (0.2)	4.8 (0.2)
Org. matter (%)	3.5 (1.3)	4.9 (1.2)	3.5 (0.6)
K (mmol.kg^{-1})	8.8 (5.0)	9.4 (1.1)	4.0 (1.5)
P-Olsen (mg.kg^{-1})	8.4 (5.7)	15.0 (4.2)	11.3 (7.4)

[a] (Erenstein, 1989)
[b] (Chin-Fo-Sieeuw, 1994)

Fo-Sieeuw, 1994) is from a fertilizer trial conducted in 1991 on a relatively fertile and an infertile soil (Table 1). Three levels of N (0–50–100 kg N.ha^{-1} as ammonium nitrate), three levels of P (0–19.6–39.3 kg P.ha^{-1} as triple superphosphate) and two levels of K (0–41.5 kg K.ha^{-1} as potassium chloride) were applied in a factorial experiment with hybrid maize. P, K and one third of the total N rate were applied when all plants had emerged. The rest of the N was applied 1.5–2 months after sowing. Emergence on the infertile soil was very poor and therefore the field was partly resown. During the experiment the weeds and insects were controlled chemically. Harvest took place 89 days after sowing on the fertile soil and 102 days after sowing on the infertile soil.

The raw data sets were re-analysed to see if nutrient concentrations would increase with increasing yield level. A considerable variation in concentrations per yield level was found (data not shown), but also at high yields low nutrient concentrations were found. Table 2 shows the minimum crop nutrient concentrations. 50% of these concentrations was not obtained at the lowest application level of that nutrient. Average nutrient concentrations (Table 2) were considerably higher in both data sets. In most cases average and minimum nutrient concentrations are higher in Data set 2, except for grain N and straw K contents. Average grain yield and harvest index (HI) in Data set 2 were also clearly lower than in Data set 1, probably due to bird damage.

For calculating the apparent fertilizer recovery only the data from Data set 2 could be used. For each combination of P and K application level, three N-application levels were available. With these three points per P and K application level, the apparent N-recovery was calculated by linear regression, because the relation between N-uptake and N-application is generally linear (Van Keulen & Van Heemst, 1982). This resulted in six estimates of the apparent N-recovery. In the same way P-recovery was calculated. Van Keulen & Van Heemst (1982) showed that the relation between P-uptake and P-application may have different forms. The data from the Atlantic Zone did not show one particular type of relation. Therefore, the most simple relation, a linear one, was used. For K too few data were available. It was expected that the apparent nutrient recovery would increase with increasing application levels of the other nutrients. However, neither a relation was found between apparent N-recovery and P and K application nor a relation between P-recovery and N and

Table 2. Average and minimum nutrient concentrations in maize in Data set 1 and 2 (standard deviation between brackets).

	Data set 1[a]	Data set 2[b]
avg. grain N%	1.77 (0.11)	1.30 (0.14)
avg. grain P%	0.25 (0.03)	0.44 (0.07)
avg. grain K%	0.34 (0.03)	0.58 (0.10)
avg. straw N%	0.82 (0.18)	0.84 (0.13)
avg. straw P%	0.09 (0.03)	0.21 (0.06)
avg. straw K%	1.70 (0.53)	1.28 (0.16)
min. grain N%	1.50	0.94
min. grain P%	0.20	0.28
min. grain K%	0.29	0.38
min. straw N%	0.42	0.51
min. straw P%	0.04	0.13
min. straw K%	0.55	0.96
no. of measurements	28	36
yield (ton ha^{-1})	3.12 (1.12)	1.92 (1.30)
harvest index	0.40 (0.06)	0.28 (0.10)
P/N ratio	0.13 (0.02)	0.30 (0.06)
K/N ratio	0.85 (0.22)	1.09 (0.13)

[a] (Erenstein, 1989)
[b] (Chin-Fo-Sieeuw, 1994)

K application. Table 3 shows the maximum apparent nutrient recoveries found. Maximum N-recovery on the infertile soil was obtained at high P and K application level. The other maximum recoveries were obtained at relatively low application levels of the other nutrients. The average apparent nutrient recoveries were calculated (Table 3), leaving out those situations where no relation was found between nutrient uptake and nutrient application level (R^2 close to zero or negative recovery). The extremely low values for R^2 and the negative recoveries were obtained on the infertile soil, where bird damage was most severe in plots with high nutrient application rates. These average recoveries are much lower than the maximum recoveries.

Comparison of data from the Atlantic Zone with data from other information sources

As shown, good data from the region are scarce. In order to judge the usefullness of the data, they are compared with data from other information sources.

In Table 4 the minimum crop nutrient concentrations mentioned by Nijhof (1987) and Van Duivenbooden (1992) are presented. Both authors made a compilation of minimum and maximum nutrient concentrations found in various crops all over the world. The minimum and maximum concentrations cover 90% of the data they found, leaving out extreme low and high values. Although minimum nutrient con-

Table 3. Maximum and average apparent fertilizer recovery fractions in Data set 2 (Chin-Fo-Sieew, 1994) in two soils (standard deviations between brackets). For way of calculation see text.

	Infertile soil	Number of measure-ments	Fertile soil	Number of measure-ments
Maximum				
N	0.66		0.62	
P	0.13		0.26	
Average				
N	0.49 (0.15)	3	0.42 (0.12)	6
P	0.06 (0.04)	4	0.14 (0.09)	4

centrations in maize from both literature sources differ considerably, the minimum concentrations in Data set 1 and 2 are generally higher than those from Nijhof and Van Duivenbooden. This can indicate that in both experiments more nutrients were taken up than were needed for growth. Plants need a certain nutrient concentration for optimal photosynthesis. It is, however, unknown whether the minimum concentrations in Table 4 are sufficient for unlimited growth. To check this, the amount of grain dry matter produced per kg nutrient uptake was calculated for the nutrient concentrations mentioned in Table 4, and compared with the minimum and maximum

Table 4. Average and minimum nutrient concentrations in maize grain and straw in the two data sets from the Atlantic Zone, compared with minimum and average concentrations from other literature sources.

	N	P	K
Grain nutrient concentration (%)			
avg. Data set 1[a] + 2[b]	1.51	0.36	0.47
avg. Van Duivenbooden	1.55	0.29	0.35
avg. De Koning *et al.*[c]	1.5	–	–
min. Data set 1 + 2	0.94	0.20	0.29
min. Nijhof[d]	0.90	0.16	0.17
min. Van Duivenbooden[e]	1.10	0.16	0.25
Straw nutrient concentration (%)			
avg. Data set 1 + 2	0.83	0.16	1.46
avg. Van Duivenbooden	0.66	0.08	1.16
avg. De Koning *et al.*	1.0	–	–
min. Data set 1 + 2	0.42	0.04	0.55
min. Nijhof	0.40	0.04	0.40
min. Van Duivenbooden	0.45	0.02	0.80

[a] Erenstein (1989)
[b] Chin-Fo-Sieeuw (1994)
[c] De Koning *et al.* (1992)
[d] Nijhof (1987)
[e] Van Duivenbooden (1992)

values from Van Keulen & Van Heemst (1982), obtained after an extensive analysis of yield uptake curves of small grains. These minimum and maximum grain dry matter productions per kg nutrient uptake were also observed for maize by Van Duivenbooden (1992) and Janssen *et al.* (1990). In Table 5 the amounts of grain produced per kg nutrient uptake are presented in case of a grain dry matter production of 8 ton ha^{-1}. This production is considered the potential for the region, based on experimental data from Foster Russell (1982) and Avila Vega (1984). The table shows that, when using the minimum concentrations from Nijhof (1987), the amount of grain produced per kg N and especially per kg K are higher than the maximum efficiencies mentioned by Van Keulen & Van Heemst (1982). This can indicate that these concentrations were measured in situations deficient in N and K. When using average nutrient concentrations sometimes minimum efficiencies are approached. The minimum concentrations from Van Duivenbooden (1992) and the Atlantic Zone itself give efficiencies closer to the maximum efficiencies from Van Keulen & Van Heemst (1982) and seem therefore the best choice for use in an explorative land use optimization study. The amount of grain produced per kg K-uptake in the Atlantic Zone is rather high (Table 5). This was caused by an extremely low K-concentration in straw on an infertile soil. The data sets with minimum nutrient concentrations from Van Duivenbooden (1992) and the Atlantic Zone show that the ratios between the macronutrients are not the same. The minimum P-concentration in the Atlantic Zone is relatively high compared with the minimum concentration found by Van Duivenbooden (1992). This could be expected, because in semi-arid regions, for which most data from Van Duivenbooden are collected, P is often in short supply. In the Atlantic Zone N is normally the most limiting nutrient, because of leaching

Table 5. Grain yield per kg nutrient uptake and P/N and K/N uptake ratios, if the concentrations from Table 3 would be used for a crop producing 8 ton/ha with a harvest index of 0.5, taking into account the minimum nutrient uptakes required before grain production can take place (5, 0.4 and 2 kg respectively for N, P and K). The efficiencies are compared with the maximum and minimum efficiencies mentioned by Van Keulen & Van Heemst (1982).

	N	P	K	P/N	K/N
	kg grain production per kg uptake				
avg. Data set 1[a] + 2[b]	44	194	52	0.22	0.82
avg. Van Duivenbooden	47	274	67	0.17	0.68
avg. De Koning *et al.*[c]	41	–	–	–	–
min. Data set 1 + 2	72	426	123	0.18	0.62
min. Nijhof[d]	81	513	183	0.15	0.44
min. Van Duivenbooden[e]	67	571	98	0.12	0.68
max. efficiency[f]	70	600	120	0.12	0.58
min. efficiency	30	200	30	0.15	1.00

[a] Erenstein (1989)
[b] Chin-Fo-Sieeuw (1994)
[c] De Koning *et al.* (1992)
[d] Nijhof (1987)
[e] Van Duivenbooden (1992)
[f] Van Keulen & Van Heemst (1982)

losses due to the high precipitation rate. Besides this, most of the nutrient concentrations have been obtained at production levels far below potential production. When using data from experiments with higher production levels different ratios may be found.

Table 6 shows data on apparent fertilizer recoveries from various sources. As can be seen, a wide range of recoveries was obtained in practice. The low recoveries have probably been obtained in situations where other production factors were limiting growth or in situations with sub-optimal management. Maximum recoveries are mostly very high, but in the Atlantic Zone, with a very high precipitation surplus these apparent recoveries will probably never be reached. The standard and average values and the estimates of the experts do not differ much. The average recoveries from the Atlantic Zone are in the same range, but these have been obtained in situations that were not always optimal. The maximum apparent recoveries from the Atlantic Zone shows that sometimese higher values can be obtained.

It can be concluded that it is doubtful that data from the Atlantic Zone on nutrient concentrations and fertilizer recoveries for maize represent the most efficient way of production in the region. Therefore, in this data scarce environment using data from other sources of information can also be justified.

Table 6. Apparent fertilizer recovery fractions of N, P and K under maize from different information sources.

	N	P	K
Average Atlantic Zone	0.44	0.10	
Maximum Atlantic Zone	0.66	0.26	
Ranges found in literature			
Baligar & Bennett (1986)	0.20–0.80	0.10–0.30	0.20–0.40
Janssen & Wienk (1990)	0.30–0.50	0.15–0.25	0.35–0.60
Van Duivenbooden (1992)	0.00–0.90	0.00–0.70	0.11–0.60
Van Keulen & Van Heemst (1982)	0.10–0.80	<0.30	0.50–0.80
Averages or standard values from literature			
Baligar & Bennett (1986)	0.50	0.10	0.40
Janssen & Wienk (1990)	0.40	0.20	0.50
Van Duivenbooden (1992)	0.36	0.18	0.34
Values used in other explorative studies			
Veeneklaas *et al.* (1993)	0.20–0.45	0.15–0.30	0.50–0.65
De Koning *et al.* (1992; potential production)	0.75	–	–
De Koning *et al.* (1992; water-limited production)	0.36–0.60	–	–
Expert estimates for the Atlantic Zone			
Schröder (pers. comm.)	0.40	–	–
Janssen (pers. comm.)	0.50	0.20	0.50

General discussion: implications for LP-models

The use of data either from literature or from the region itself, and the use of either the approach with constant nutrient concentrations or that with increasing nutrient concentrations greatly influence the value of the input-output coefficients and thus the outcome of the land use optimization study, especially if in the LP-model the availability of fertilizers is restricted or if the model is optimized for efficient use of fertilizers. If constant nutrient concentrations are used and the model is optimized for fertilizer use efficiency, the LP-model will select production systems with high production levels. In case of increasing nutrient concentrations with increasing yield levels, the LP-model will select relatively lower production levels, because then fertilizers are used more efficiently. When using minimum nutrient concentrations instead of average concentrations, production can be higher with the same amount of nutrients. As can be expected, the effect of uncertainties will strongly depend on the restrictions and objectives used in the LP-model.

The general purpose of LP-models is to increase the amount and quality of the information for decision-makers to base their decisions on. The results of LP-models and uncertainties in model coefficients should therefore be seen as complementary. So when uncertainties exists, these should be made visible. To obtain an indication of the effect of the uncertainties on the final scenarios produced by a LP-model, the model can be run with all logical combinations of estimates for technical coefficients. However, since there are usually many parameters in LP-models, this is nearly impossible. Tools suitable for sensitivity analysis in simulation models can probably also be used in LP-models. They can save time by finding those parameters for which the model is sensitive. If the model is run with 'optimistic' and 'pessimistic' estimates of these parameters, at least an indication of the degree in which the presented information is 'not certain' can be derived (Voogd, 1980). Uncertainty is probably an inevitable element in modeling, but making it explicit might well help to develop better insight in the margins of the scenarios.

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