Netherlands Journal of Agricultural Science 48 (2000) 273-290

A methodology to support the decision to invest in spatially variable nitrogen fertilisation

A.B. SMIT[1,*], J.J. STOORVOGEL[2] AND G.A.A. WOSSINK[1,3]

[1] Wageningen University, Department of Social Sciences, Hollandseweg 1, NL-6706 KN Wageningen, The Netherlands.
[2] Wageningen Agricultural University, Laboratory of Soil Science and Geology, P.O. Box 37, NL-6700 AA Wageningen, The Netherlands.
[3] North Carolina State University, Department of Agricultural & Resource Economics, Campus Box 8109, Raleigh, NC 27695, USA.
* Corresponding author; current address: Agricultural Economics Research Institute (LEI), P.O. Box 2176, NL-8203 AD Lelystad, The Netherlands (fax: +31 320 293595; e-mail: a.b.smit@lei.wag-ur.nl).

Received 17 May 1999; accepted 17 November 2000

Abstract

This paper reports a methodology to define and select basic activities for spatially variable N-management, referred to as management tracks. Their main purpose is to support decision making whether or not to apply variable nitrogen fertilisation. The methodology is based on biophysical simulation of crop growth and nitrogen leaching (WAVE) in combination with economic optimisation (linear programming) and enables a normative environmental-economic evaluation of site specific N-management to be made. The partial results of a case study with an input-intensive and an input-extensive crop (ware potato and winter wheat, respectively) showed that site specific nitrogen management led to positive returns over variable costs compared to uniform N-application, conditional on the validity of the WAVE model used in simulating yield effects. The investments that could be allowed for at maximum were 6,300 Dfl and 13,500 Dfl for winter wheat and ware potato, respectively, assuming application to an area of 100 ha. A pollution tax or a tax on nitrogen designed to internalise pollution costs in agricultural production raises these maximum amounts to 7,600 and 33,700 Dfl, respectively. Practical feasibility requires site-specific nitrogen management to be integrated with time specific management since optimal N-tracks were found to be highly weather dependent. Besides, spatially variable management cannot be achieved unless good farming practices (soil testing and crop scouting) are already in place.

Keywords: site specific management, sustainability, nitrogen fertiliser, water quality, risk

Introduction

Site specific management (SSM), or sub field management, bases crop management on the spatial variability of agronomic characteristics (soil, crop, pests) that are present in most fields (Verhagen, 1997). SSM is the spatial component of precision agriculture. The temporal fine-tuning of crop management is the other aspect of precision agriculture that may result in a more efficient nutrient management (Van Alphen & Stoorvogel, 2000b). To register and manage field variability, SSM uses global positioning systems (GPS) together with geographical information systems (GIS) and specialised equipment. Management decisions in precision farming have strategic, tactical and operational dimensions (Bouma, 1997a). In this paper we focus on the tactical aspects of SSM. Tactical decisions are taken before the growing season and deal with cropping plan, selection of varieties or the choice between uniform and SSM-application of nutrients and pesticides (Smit, 1996).

Variable management within fields holds the promise of both economic and environmental benefits through improved input productivity (or input use efficiency). A related, third possible benefit is reduction of the management risks incurred by variable weather conditions, *i.e.* when more stable yields stabilise net revenue over time and when peaks in nitrogen leaching can be prevented. SSM reduces the variability in growing conditions and could thereby reduce the variability in yield and in nitrogen emission.

The objective of this paper is a methodology that makes it possible to compare uniform and SSM-application of chemical nitrogen fertiliser in arable crops under Dutch conditions. Specifically, we present a methodology to determine and select basic activities for N-application, referred to as management tracks. Their main purpose is to support decision-making in precision agriculture, *i.e.* the decision whether or not to apply SSM. Our approach combines biophysical simulation with economic optimisation and enables a normative environmental-economic evaluation of site specific N-management to be made. First, we assess management tracks both for uniform and site-specific nitrogen application by means of simulation. Second, the results of the biophysical simulations are gathered in a linear programming model of profit maximising N-management that selects the optimal tracks. Next, the optimal tracks are used to assess the financial and environmental net benefits of site specific N-management for individual crops. The two main questions in the economic evaluation are (1) to quantify the positive returns over variable costs of SSM compared to uniform N-application, and (2) what variable and fixed costs and investments (additional labour, sampling and equipment) would be allowed for at maximum.

The methodology was applied for an input-intensive and an input-extensive crop (ware potato and winter wheat, respectively) on a commercial farm located in the South-western part of The Netherlands. Arable farming in this part of The Netherlands is characterised by rotations of mainly potato, sugar beet and winter wheat and relatively small fields (between 5 ha and 25 ha). The economics accompanying SSM depend on the ecophysiological parameters that determine crop-soil variables and farmers' N-management activities. The ecophysiological parameters are largely influenced by weather variables (rainfall, temperature and radiation) that vary from year to year. This variation and its impact on SSM economics were given special attention in this study.

Materials and methods

The methodology developed is visualised in Figure 1. Following Van Alphen and Stoorvogel (2000a), management units are defined as areas within a field with identical growing conditions; they are discerned through a detailed soil inventory and a mechanistic crop-soil simulation model providing estimations on crop production and nitrogen leaching for individual soil sampling locations. These point observations are classified to a limited number of management units. More information on the methodology applied is given in Van Alphen and Stoorvogel (2000a). Next, simulations are carried out for various N-management options (management tracks) for each management unit separately using climatic records from a weather station. The resulting data provide input for a linear programming model of N-management at the field level. This optimisation procedure then assesses the optimal track for each management unit.

Management tracks
The notion 'management track' plays an important role in the analysis of site-specific management (Bouma, 1997b). In our case, a management track is defined as the combination of timing, dose and way of application of chemical nitrogen (N). Timing deals with the number of applications, since in many crops splitting of N is applied, and the dates of application. The total dose can be divided into two or more split applications, which may differ in size. The method of application can be broadcast or row application. In this paper, only the more common way of broadcast application is taken into account.

Besides input variables, a management track is defined by output variables – measured, calculated or assessed by simulation – characterising different aspects of sus-

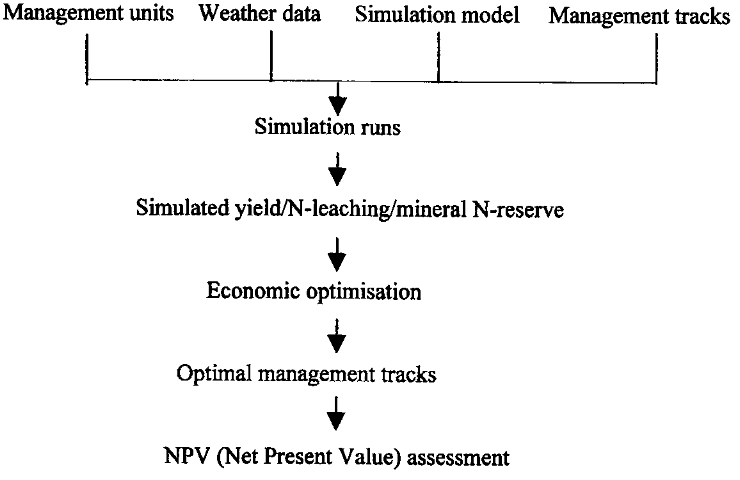

Figure 1. The methodology for the ex-ante assessment of the economic perspectives of precision agriculture.

tainability; see Stoorvogel *et al.* (2001). In this study, five output variables were included:

(1) yield: in the case of winter wheat, fresh yield with a standard moisture content of 15%; in the case of ware potato, dry matter yield, which was transferred into fresh weight, assuming a dry matter content of 21%; in kg ha^{-1};
(2) variable costs and returns over variable costs, in Dfl ha^{-1} (Dfl = Dutch guilder; 1 Dfl ≈ 0.5 US$);
(3) post-harvest N-leaching, *i.e.* between harvest and 1 January of the next year, in kg ha^{-1};
(4) post-harvest mineral N-reserve in the rooted soil zone, having a depth of 100 cm for winter wheat and of 60 cm for ware potato, in kg ha^{-1}; the N-reserves are linked to the uptake zones of the different crops.
(5) risks on a) low returns over variable costs, b) high post-harvest N-leaching, and c) high post-harvest mineral N-reserves; all in %.

We will return to the assessment of these output variables by simulation later on. The identification and selection of the management tracks was mainly based on N-fertilisation schemes in crop grower's handbooks; besides, alternative tracks were formulated through adaptations of the total dose of N applied and of the number and dates of application. The adaptations were selected in such a way that changes in output (yield, N-losses, risks) were expected to be found.

Simulation model

Local growing conditions were simulated using the mechanistic, deterministic WAVE model (Water and Agrochemicals in soil and Vadose Environment, Vanclooster *et al.*, 1994). WAVE integrates four existing models; one dimensional soil water flow based on SWATRER (Dierckx *et al.*, 1986), nitrogen cycling based on SOILN (Bergström *et al.*, 1991), heat and solute transport based on LEACHM (Wagenet & Hutson, 1989) and crop growth based on SUCROS (Spitters *et al.*, 1989).

WAVE requires input data on crop, soil type, planting and fertilisation dates and doses, i.e. data that define the input variables of the different management tracks. The basic simulation runs concerned weather data of an average (1983), a wet (1987) and a dry year (1996). The amounts of mineral N available measured at the fields in February 1997 served as input for WAVE. 100 Kg N ha^{-1} and 116 kg N ha^{-1} in the soil layer 0–100 cm was observed for fields 6 and 2, respectively, which is rather high compared to average values of other years (51 kg ha^{-1} according to Smit *et al.*, 1995). The simulations were carried out for both winter wheat and ware potato. Therefore, the basis simulation runs were carried out for 2 fields * 2 crops * 12 management units * 15 management tracks * 3 weather types, which brought the total number of runs up to 2160.

The study fields

The study was done for two fields ('field 6' (11.6 ha) and 'field 2' (9.9 ha)) at the commercial arable farm of the Van Bergeijk family on light clay soils in the Southwestern part of The Netherlands; see Van Alphen & Stoorvogel (2000a) for a description. In previous research, a detailed 1:5000 soil survey had been done at the

Van Bergeijk farm, accounting approximately 6 soil samples per hectare (Van Alphen and Stoorvogel, 2000a). The soil maps showed that field 6 had more variation than field 2, especially in organic matter content.

The fields were divided in management units by means of a pre-run of the biophysical simulation model for extreme (very dry or very wet) conditions at point level. Management units are defined as areas within a field with identical growing conditions (Van Alphen & Stoorvogel, 2000a) and can be assessed by combining those simulation points with similar reactions to extreme weather conditions. Fields 6 and 2 were divided in 12 units, composed of 2 yield classes * 2 N-leaching classes * 3 N-reserve classes. These management units explained more than 75% of the observed variation.

Assessment of the output variables of the management tracks

Part of the output variables of the management tracks was directly generated by WAVE (yield, post-harvest N-leaching and post-harvest N-reserve); other variables required an additional assessment. To assess the output variables on costs and risks, calculations had to be done based on the results of the simulations. The costs of N-fertiliser were determined as the total N-rate proposed in the track, times the price per kg N fertiliser. Product prices were taken from Spigt *et al.* (1997) and were based on the average farmers' prices in the last several years for the region South-western Clay Region. Some of the other cost items in the overview published, like costs of drying, cleaning, insurance and interest, are yield-dependent but small and fixed figures have been used in our calculations. The variable costs were considered to be equal for all weather types, except those of fungicides; in the wet and dry years, double and half doses respectively were applied in comparison to the average year. This rule of thumb can be observed in practice, especially in ware potato growing, where the period between two successive sprayings against Phytophthora infestans is doubled in dry years and halved in wet years (Janssen, 1996).

The gross revenues, required to calculate the returns over variable costs, were calculated as (marketable) yield * product price. We used 0.25 Dfl kg^{-1} and 0.20 Dfl kg^{-1} as basic product prices for winter wheat and ware potato, respectively. In the case of winter wheat, the revenues calculated were raised with a fixed (i.e. yield-independent) straw yield of 465 Dfl ha^{-1} and an EU-compensation of 847 Dfl ha^{-1}, assuming that the farmer fulfilled the relevant legal requirements (Spigt *et al.*, 1997).

For the assessment of the changes in environmental risks we defined thresholds for 'high N-leaching' and 'high N-reserve' as 'above 20 kg ha^{-1}' and 'above 42 kg ha^{-1}', respectively for both crops. The threshold value for 'high N-leaching' was selected in such a way that about 10% of the tracks studied had higher N-leaching outcomes in preliminary WAVE-simulations. The value for 'high N-reserve' represents the threshold to be regarded to avoid nitrate contents of more than 50 mg l^{-1} in ground water, which is the E.U.-threshold (Verhagen, 1997). To assess the risk variables, one track for each crop was analysed in detail with weather input of a series of 15 years (1983–1997). From the time series runs over 15 years, frequency distributions of yield, N-leaching and N-reserve were derived for the crops, the field and the management track studied. From the distributions, the probabilities or risks that the yield, the N-leaching and the N-reserve would be lower, equal and higher respectively than acceptable levels were calculated. For the latter two variables, the associated frequency distributions provided the probabilities. Next, risks were assessed for the other 14 tracks studied using the average values of 4 points * 15 years. For every track, the N-leaching and N-reserve values simulated were divided by the corresponding average values of the 60 points in the time series and multiplied with the corresponding probability.

For the calculation of risks on returns over variable costs, an extra calculation had to be made. Assuming farmer's income objective to maximise returns over variable costs, minimum levels were set at 2,500 Dfl ha^{-1} and 8,000 Dfl ha^{-1} for winter wheat and ware potato, respectively (selected in such a way that about 10% of the tracks studied had lower returns over variable costs). From these net returns, minimum yield levels were calculated, which were different per track, since the variable costs differed per track. Moreover, both the calculated yield level and calculated variable costs differed for the three weather types. The probability of not reaching a certain yield was derived from the frequency distributions. We assumed that the frequency distributions of yield, N-leaching and N-reserve were the same for field 2 and field 6.

Linear programming

The direct and indirect results of WAVE-runs were included in a linear programming (l.p.) model. This type of model is frequently used for decision support in farm management, particularly when environmental aspects are involved; see *e.g.* Verhoeven *et al.* (1995) and Wossink & Rossing (1998). A generic formulation is (Pannell, 1997):

$$Max\ Z = c'x$$

$$\text{subject to } Ax \leq b \quad , \quad x \geq 0$$

The l.p. model maximises Z, the total returns over variable costs over the total field, i.e. summed over all management units; x is the vector of management tracks (or the areas cultivated according to the management tracks) for each of the various management units at the field, c' is the matrix with prices of inputs and outputs, and A is the matrix of input and output characteristics of the management tracks. The vector of constraints, b, includes the available area per management unit and, optionally, pre-set thresholds for the N-leaching and/or N-reserve figures and/or the risks that maximum values for one or both of these would be exceeded and/or the risk that minimum returns over variable costs would not be reached.

Uniform and SSM-applications of nitrogen were compared through a series of 24 l.p. calculations (2 fields * 2 crops * 3 weather types * 2 tactics (uniform or SSM) = 24 l.p. runs). In the case of uniform application, in which management units were not separately optimised, weighed averages of coefficients per management track (yields, leaching figures, reserves, risks, returns over variable costs, etc.) were calculated for the total field. N-fertilisation was then optimised based on average coefficients. With SSM application, we selected the optimal track per unit and afterwards the coefficients of the tracks selected were weighed. To assure that only one track per management unit was selected, a boolean variable was included in the l.p. model.

To study the profitability of SSM under different market and policy conditions, the series of 24 l.p. calculations was repeated for two alternative scenarios: (1) an output price cut scenario and (2) an emissions levy scenario. In the first scenario, product prices of winter wheat and ware potato were lowered to 0.20 Dfl kg^{-1} and 0.15 Dfl kg^{-1}, respectively. In the second scenario, the original product prices were applied, but a more or less arbitrary levy of 10 Dfl (kg N leached)$^{-1}$ was introduced.

Returns to investment

Besides potential for yield increase and reduced input use, key factors in SSM profitability are the acreage over which the fixed costs can be spread and the amortisation period over which soil testing, mapping costs and equipment can be used (Lowenberg-De Boer & Aghib, 1997). The two tactics (uniform versus SSM) may lead to differences in average figures per ha for yield, variable costs and returns over variable costs, and the various risks discussed. Maximum investments to be allowed for were calculated from the extra returns over variable costs. We used the net present value method (see *e.g.* Hickman *et al.*, 1996) with an interest rate of 4% (Anonymous, 1997), a depreciation term of 10 years and possible application of SSM at an area of 100 ha. Additional mapping, soil sampling and labour costs were not taken into account.

Results

Management tracks

In total, 15 management tracks were defined, differing in total N-rate, and in number, dose and timing of (split) applications. For each field, there were 12 * 15 = 180 management tracks. In winter wheat, the total N-rate and number of split applications varied between 70 kg ha^{-1} and 300 kg ha^{-1} and between 2 and 5, respectively. In ware potato, the N-fertilisation rates and the number of applications were 60 kg ha^{-1} – 360 kg ha^{-1} and 1–3, respectively (Tables 1A and 1B).

Figures 2A and 2B show results of the WAVE simulations for kernel yields and N-leaching N-reserves respectively for winter wheat at field 6 in an average year. The graphs for field 2 and for potato grown on both fields are comparable and not included here. Note: In Figures 2A and 2B, two points per unit are given at an N-rate of 270 kg ha^{-1}; this is due to two timing alternatives of fertiliser applications. Most N-rates/management tracks simulated gave yields in the horizontal parts of the curves. Notice that there is a significant variation between management units in the responses to additional N in the range of 70 kg ha^{-1} to 180 kg ha^{-1}. Therefore, differences can be expected in optimal N-rates between uniform and SSM application particularly in this range. As visualised in Figure 2B, N-leaching widely differed at the different management units of field 6. Some units showed relatively high N-leaching

Table 1A. Management tracks with two to five N-applications in winter wheat. References: De Jong (1986); Spigt *et al.* (1997); Darwinkel & Zwanepol (1997); W. Stol (PRI, pers. comm., 1997).

Track number	N-application rates at different crop growth stages[1] (kg ha^{-1})					Total N-rate (kg ha^{-1})
	Starting date[2]	F5	F6–7	F8	F9–10	
1	40	0	30	0	40	110
2	40	0	30	0	0	70
3	80	0	30	0	40	150
4	80	0	30	60	40	210
5	80	0	60	0	40	180
6	80	0	60	60	40	240
7	80	30	30	0	40	180
8	80	30	30	60	40	240
9	80	30	60	0	40	210
10	80	30	60	60	40	270
11	80	60	30	0	40	210
12	80	60	30	60	40	270
13	80	60	60	0	40	240
14	80	60	60	60	40	300
15	80	0	180	0	40	300

[1] We assumed a basic application before the growing season (as soon as soil and weather conditions allow application without damage to crop or soil ('workability'; Van Wijk & Buitendijk, 1988)) and one to four additional (split) applications during the season; F-stages refer to the development scale of Feekes, which is included in many textbooks on wheat, *e.g.* Darwinkel & Zwanepol (1997). DVS means 'development stage', being a mainly temperature-driven variable in model WAVE.
F5 = DVS 0.41: the leaf sheaths are strongly erected;
F6–7 = DVS 0.50: one or two nodes are observed;
F8 = DVS 0.64: the last leaf just becomes visible;
F9–10 = DVS 0.82: just before the ear appears.

[2] Assuming a required level of (140 kg ha^{-1} – $N_{min,0-100\,cm}$) and $N_{min,0-100\,cm}$ = 60 kg ha^{-1}.

figures for N-rates over 150 kg ha^{-1}. Variation in field 2 was found to be similar.

The results as presented in Figures 2A and 2B were used to calculate the returns over variable costs for each of the N-rates/management tracks applied at the 12 management units of field 6 (Figure 3). The maximum net returns varied between 2,900 Dfl ha^{-1} and 3,000 Dfl ha^{-1} and were achieved at N-rates of 70 kg ha^{-1}, 110 kg ha^{-1}, 150 kg ha^{-1} or 180 kg ha^{-1} depending on the management unit. Some management units appeared to be particularly sensitive to N-rates below 150 kg ha^{-1} and showed large reductions in net returns compared to the associated maximum level. Three more sets of results were generated, namely for wheat at field 2 and for ware potato grown at fields 2 and 6 (not presented here). Fields 2 and 6 had different organic matter contents; this had its effect on within-field differences in mineralisation capacity, which was included in the simulation.

Economic optimisation of N-fertilisation

Figure 3 presents results for wheat, an average weather year and field 6. These outcomes and those for ware potato, field 2 and dry and wet years were used in the basis

Table 1B. Management tracks with one to three N-applications in ware potato. Reference: Van Loon *et al.* (1993).

Track number	N-application rates at different crop growth stages[1] (kg ha^{-1})			Total N-rate (kg ha^{-1})
	Starting date[2]	D2	D3	
1	90	0	0	90
2	60	0	0	60
3	120	0	0	120
4	120	40	0	160
5	120	40	40	200
6	120	80	0	200
7	120	80	40	240
8	160	0	0	160
9	160	40	0	200
10	160	40	40	240
11	160	80	0	240
12	160	80	40	280
13	200	80	0	280
14	200	80	40	320
15	200	80	80	360

[1] We assumed a basic application just before or after planting and one or two additional applications after emergence:
D2 = start of tuber formation;
D3 = additional application 3 weeks later.

[2] Assuming a required level of (265 kg ha^{-1} – 1.1*$N_{min,0-60\ cm}$) (being the average equation of yield and quality focused recommendations, respectively) and $N_{min,0-60\ cm}$ = 60 kg ha^{-1} on clay soil.

series of 24 l.p. calculations to assess the differences between uniform and SSM-applications of nitrogen, as discussed earlier. Table 2 gives the resulting average optimal N-rates/management tracks for either uniform or SSM application.

For all crop/weather type combinations except one (winter wheat/wet), the optimal N-rate for uniform application was the same for the two fields. For three out of four objects with an average or wet weather type, SSM had a higher or equal optimum N-rate compared to the corresponding uniform treatment. In the dry year, three out of four objects had a lower or equal optimum N-rate in the SSM-case. Further analysis showed that in case of higher average optimal N-rates for SSM compared to uniform application, the SSM-objects had higher kernel or tuber yields, higher post-harvest N-leaching and mineral N-reserves and increased risks of high N-leaching and N-reserve (data not given). In case of lower average optimal N-rates for SSM compared to uniform application, the SSM-objects always had lower figures for post-harvest N-leaching and mineral N-reserves and for the risks. However, the kernel or tuber yields were not necessarily lower than in uniform treatments but in some cases even higher, which suggests a more effective utilisation of the nitrogen applied to the different soil units.

Tables 3A and 3B summarise the effects of SSM in winter wheat and ware potato; they give average figures for both crops separately, weighed over weather types and over fields. The likelihood of the average, wet and dry years was assumed to be 50%,

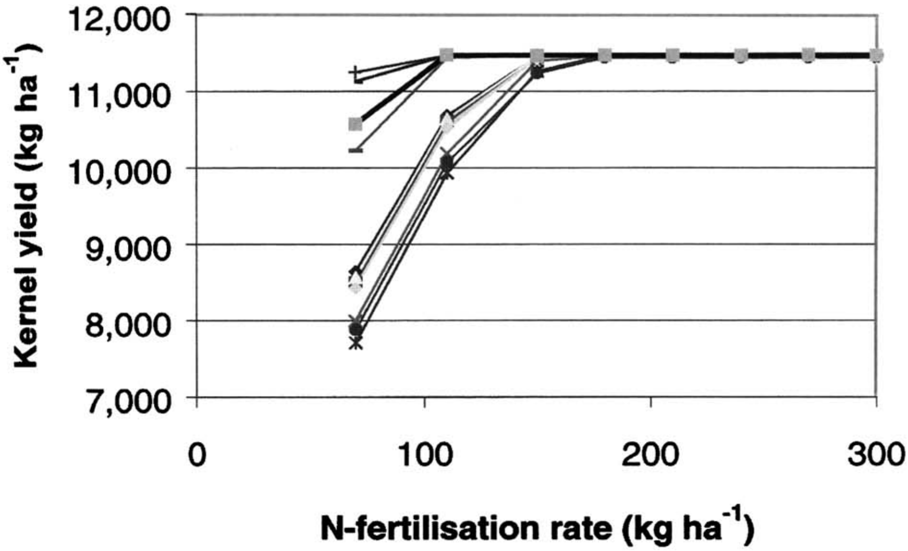

Figure 2A. Kernel yield of winter wheat at field 6 in an average year (1983) vs. N-fertilisation rate. Simulation results of WAVE. Different sets of points represent different management units.

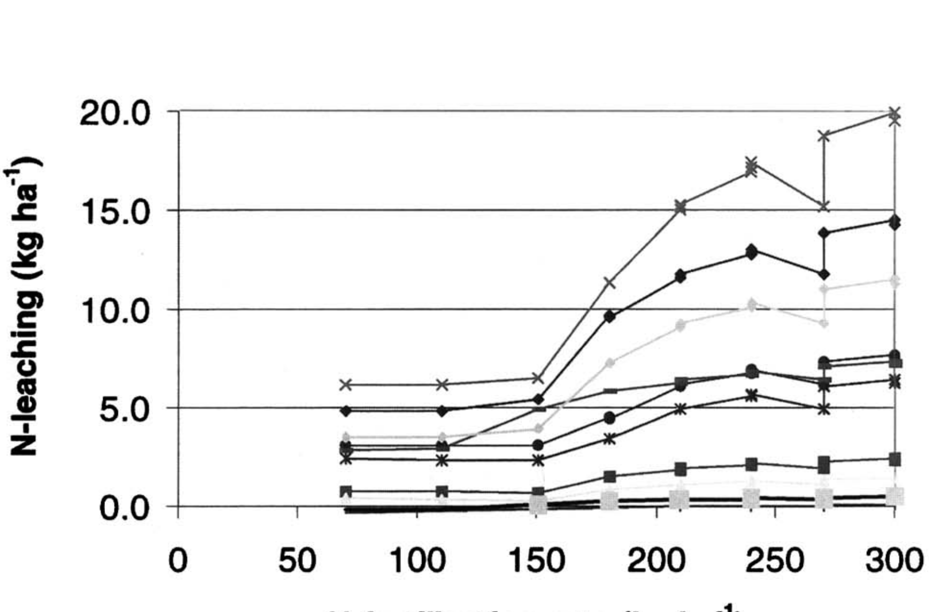

Figure 2B. N-leaching (absolute values) in winter wheat at field 6 in an average year (1983) vs. N-fertilisation rate. Simulation results of WAVE. Different sets of points represent different management units. In some cases, negative leaching (net increase of available nitrogen) was simulated.

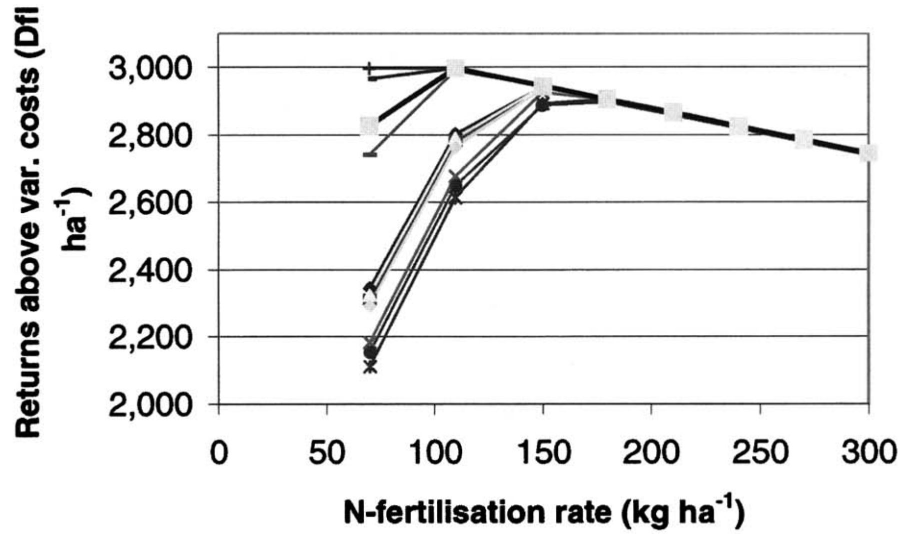

Figure 3. Returns over variable costs of winter wheat at field 6 in an average year (1983) vs. N-fertilisation rate. Based on simulation results of WAVE. Different sets of points represent different management units.

25% and 25%, and the total areas of fields 6 and 2 were taken into account, being 11.9 ha and 9.9 ha, respectively. Table 3A shows that, conditional on the validity of the WAVE simulations, SSM improved different aspects of sustainability: (1) yield increased, (2) returns over variable costs increased, (3) N-leaching decreased, and (4) the risks on high N-leaching or high N-reserves decreased. For the other aspects, results deteriorated: (1) the risk of low returns increased, and (2) the average N-input increased. However, the changes were relatively small. In Table 3B, most effects of SSM have the same sign as in Table 3A. However, in potato growing (1) the variable costs decreased as a result of a decreasing N-rate, (2) the N-reserve decreased, and

Table 2. Average optimal N-rates in winter wheat and ware potato at two fields of the Van Bergeijk farm, Voorne-Putten, simulated with WAVE and optimised with linear programming for three weather types and two tactics: uniform and SSM-application of chemical N-fertiliser.

Object (crop/field combination)	Optimal N-fertilisation rate (kg ha^{-1}) with weather type:					
	Average		Wet		Dry	
	Uniform	SSM	Uniform	SSM	Uniform	SSM
Winter wheat, field 6	150	162	150	132	110	118
Winter wheat, field 2	150	156	110	120	110	110
Ware potato, field 6	160	143	160	171	120	107
Ware potato, field 2	160	160	160	168	120	119

Table 3A. Average effects of SSM in winter wheat growing, weighed over two fields and over three years or weather types (explained in the text).

Variable	Method of N-fertilisation		Effects of SSM
	Uniform[1]	Site specific	
Kernel yield (kg ha^{-1})	10,864	10,919	+ 55
Variable costs (Dfl ha^{-1})	1,241	1,247	+ 6
Returns (Dfl ha^{-1}) [2]	2,789	2,795	+ 8
N-leaching (kg N ha^{-1})	8.4	8.3	−0.1
N-reserve (kg N ha^{-1})	31.6	31.6	0
Risks on:			
Low returns (%) [3]	7.1	7.2	+ 0.1
High N-leaching (%) [4]	17.5	17.2	− 0.4
High N-reserves (%) [5]	29.6	29.4	− 0.2
Average N-rate (kg N ha^{-1})	135	140	+ 4

[1] The field studied is treated as a uniform management unit. Each management unit of the fields studied has its own coefficients for output variables (yield, costs, N-losses, etc.), which were used to optimise each unit. The results of the SSM column were calculated as weighed averages over area. In the case of uniform treatment, the coefficients of each output variable were first weighed over area and afterwards the field as a whole was optimised.

[2] over variable costs.

[3] less than 2,500 Dfl ha^{-1}.

[4] higher than 20 kg ha^{-1}.

[5] higher than 42 kg ha^{-1}.

Table 3B. Average effects of SSM in ware potato growing, weighed over two fields and over three years or weather types (explained in the text).

Variable	Method of N-fertilisation		Effects of SSM
	Uniform[1]	Site specific	
Tuber yield (kg ha^{-1})	60,217	60,268	+ 51
Variable costs (Dfl ha^{-1})	3,432	3,425	− 6
Returns (Dfl ha^{-1}) [2]	8,612	8,628	+ 16
N-leaching (kg N ha^{-1})	22	21	− 1.0
N-reserve (kg N ha^{-1})	41	35	− 5.7
Risks on:			
Low returns (%) [3]	24	24	− 0.1
High N-leaching (%) [4]	23	22	− 1.0
High N-reserves (%) [5]	35	33	− 2.5
Average N-rate (kg N ha^{-1})	150	146	− 4

[1,2,4,5] see Table 3A.

[3] less than 8,000 Dfl ha^{-1}.

(3) the risk of low returns decreased. The increase in returns was 16 Dfl ha^{-1}, which was about twice the net returns in winter wheat. More details on the changes in N-leaching in the different crop/field/weather type combinations are given in Table 4.

Table 4 shows that the effect of SSM on N-leaching was different with (1) different weather types, (2) different crops, and (3) different fields. Remarkably, the average N-leaching over two fields increased in the average and dry years in the case of winter wheat and decreased in the case of ware potato. For the wet year, an increase was found for ware potato and a decrease for winter wheat, although the latter effect was different for fields 6 and 2. A similar risk analysis was carried out for returns over variable costs (Table 5).

Table 5 shows that the effect of SSM on returns was always nil or positive, since the uniform treatment formed the lowest level of opportunities. As with N-leaching, the effects of SSM were different with (1) different weather types, (2) different crops, and (3) different fields. The average effect over fields was highest in the wet year for both crops. The differences were large for ware potato in both the wet and dry years, but not for winter wheat in the dry year. In general, SSM in field 2 showed

Table 4. Average effects of SSM on post-harvest (harvest – 1 January) N-leaching (in kg ha^{-1}) compared to uniform N-fertilisation.

Crop/field	Winter wheat			Ware potato		
	Weather type			Weather type		
	Average	Wet	Dry	Average	Wet	Dry
Field 6	+ 0.6	– 5.8	+ 1.1	– 4.0	+ 5.5	– 6.6
Field 2	+ 0.4	+ 2.1	0	– 0.1	+ 3.0	– 0.5
Average [1]	+ 0.5	– 2.2	+ 0.6	– 2.2	+ 4.4	– 3.8

[1] weighed over the respective areas of two fields.

Table 5. Average effects of SSM returns over variable costs (in Dfl ha^{-1}) compared to uniform N-fertilisation.

Crop/field	Winter wheat			Ware potato		
	Weather type			Weather type		
	Average	Wet	Dry	Average	Wet	Dry
Field 6	+ 9	+ 22	+ 6	+ 15	+ 24	+ 38
Field 2	+ 1	+ 11	0	0	+ 23	+ 4
Average [1]	+ 5	+ 17	+ 3	+ 8	+ 24	+ 23
Overall average [2]		+ 8			+ 16	

[1] weighed over the respective areas of two fields.
[2] weighed over the respective areas of two fields and the three weather types.

less profit than in field 6, although the difference between both fields was small for ware potato in the wet year.

In alternative scenario 1, the output price cut scenario, optimal track selection did not change and hence only the financial differences between uniform and SSM-applications decreased. The results of scenario 2 with an emission levy are given in Table 6. In this case, the selection of tracks did change for a number of management units. Returns over variable costs changed too, depending on the relevant N-leaching figures. The results of the levy-study enable a trade-off assessment of N-leaching and returns, which can be important in governmental policy-making. According to our calculations, a levy of 10 Dfl ha^{-1} led in general to a decrease of post-harvest N-leaching of 1.2 kg ha^{-1} and 4.0 kg ha^{-1} for winter wheat and ware potato, respectively. The weighed decrease in returns per kg N-leached reduced was 81 Dfl kg^{-1} and 53 Dfl kg^{-1} for winter wheat and ware potato, respectively.

Maximum investments

Table 5 shows that the average increase of returns over fields and weather types was 8 Dfl ha^{-1} and 16 Dfl ha^{-1} for winter wheat and ware potato, respectively. The additional returns listed translate into maximum costs and investments in precision farming equipment of 6,300 Dfl and 13,500 Dfl for an area of 100 ha winter wheat and ware potato, respectively.

Lower product prices will decrease the extra returns from SSM – assuming that all other factors stay constant, especially the level of variable costs and the N-use efficiency of different (new) varieties (results not listed). The opposite conclusion holds for the case of stricter environmental regulations. Under scenario 2, the weighed increase in returns over fields and weather types was 9 Dfl ha^{-1} and 40 Dfl ha^{-1} in winter wheat and potato growing, respectively. In scenario 2, SSM of nitrogen would still be profitable at additional costs and investments up to 7,600 and 33,700 Dfl, respectively with application at 100 ha.

Table 6. Average effects of SSM returns over variable costs (in Dfl ha^{-1}) compared to uniform N-fertilisation in the case of an emission levy.

Crop/field	Winter wheat			Ware potato		
	Weather type			Weather type		
	Average	Wet	Dry	Average	Wet	Dry
Field 6	+ 5	+ 39	+ 16	+ 70	+ 40	+ 115
Field 2	0	0	0	+ 15	+ 2	+ 38
Average [1]	+ 3	+ 21	+ 9	+ 38	+ 22	+ 62
Overall average [2]		+ 9			+ 40	

[1] weighed over the respective areas of two fields.
[2] weighed over the respective areas of two fields and the three weather types.

Discussion

Interpretation of the results

The results presented refer to specific fields and conditions and to two specific crops. Taking into account different fields, different years, different crops, different additional sampling costs, different scenarios, additional labour costs and last but not least different biophysical simulation models could affect the calculated results of SSM. We assumed that WAVE produced reliable results concerning crop growth, the response of wheat and potato to different regimes of timing of N, and the soil N budget, including denitrification. This assumption was supported by various findings by Van Alphen & Stoorvogel (2000a,b), who compared observed and WAVE simulation results during the growing season for the same fields and crops as in this model study. In some cases, crop growth was overestimated; this could be explained by disease losses, which were not included in the model. But even if the model results were less reliable, the logic remains that input optimisation per soil unit must result in equal or (most likely) better overall results than uniform whole field treatments.

The crop response function in the biophysical simulation model is decisive for the assessment of the management tracks. Particularly, this function should have a high resolution for N-rates close to the economic optimum; see *e.g.* De Koeijer et al. (1998). Fine-tuning of tracks (especially of total N-rates) near the economic optimum may give a more refined selection of tracks. However, it is uncertain that such would give higher increases of returns for SSM, because also improvement of the uniform treatments could be expected. The shape of the crop response curve is also crucial to the discussion whether SSM leads to higher or lower N-rates on fertile and less fertile units in the field, respectively. We found no unequivocal answer – SSM could lead to higher, equal or lower N-rates in both fertile and less fertile units, depending on the shape of the production curve.

The literature generally emphasises the variations in soil characteristics and the type of crop as two key factors deciding the benefits of SSM (Robert *et al.*, 1995). Field 6 had a higher degree of variability than field 2, especially in organic matter content, and we indeed found that returns to SSM were higher at field 6 in all three scenarios for both crops. However, frequently the same tracks were optimal for the different management units, although the potential and actual yield levels were very different (Probably, this is partly the result of the limited number of tracks). So, it is not the variability in soil characteristics that determines returns to SSM but merely the variability among management units in crop response. Several studies have also noted that the economics of SSM will be biased towards input-intensive crops, that is that the profitability is higher for crops with higher levels of input use (see *e.g.* Lowenberg-De Boer and Boehlje, 1996). SSM in ware potato (with returns of about 6,000 Dfl ha^{-1} – 9,000 Dfl ha^{-1}) was indeed more profitable than in winter wheat (with returns between 2,500 Dfl ha^{-1} and 3,000 Dfl ha^{-1} in all scenarios).

Partial analysis

The major challenge of the evaluation of SSM is to account fully for all benefits and costs. Benefits can take many forms. The only benefits we measured are single year yields and cost and yield changes for two crops and only one input. Our analysis is therefore partial, as is common with economic studies of SSM; see the overview presented by Lowenberg-DeBoer & Swinton (1997). Other potential benefits are carry-over fertiliser effects, improved quality of produce and the effects of managing multiple inputs with the same SSM investment. Baking quality of winter wheat and tuber size distribution of ware potato affect product price and thus returns. SSM may also become more profitable when other nutrients and biocides are included. However, more equipment will then be required and the division of fields in management units may become more complicated. Additional research (also in a technical sense) is required to complete the overview of possible SSM benefits.

Linear programming
N-response curves are typically non-linear. This means that they have to be approximated. This can be done by describing a limited number of management tracks. Consequently, the methodology depends heavily on the definition of these management tracks. In this specific study the N-response curve is described by 15 different management tracks. The crop-response to increased fertilisation (Figure 2A) shows that few options were given to the model in the trajectory of the curve where effects can be expected (between 75–150 kg ha^{-1}). Additional management tracks in this part of the curve may increase the positive effect of SSM.

Use in practice
Good spatially variable management cannot be achieved unless good farming practices, particularly soil testing and crop scouting, are already in place (Schueller, 1996). SSM would require even higher managerial skills of computer and data use. Besides, time specific management is required. Our analysis showed that the optimal N-fertilisation tracks selected differed over years or weather types. Therefore, it is not possible to assess the best tracks beforehand and to blindly apply them during the season. Time-specific management, as studied by Van Alphen & Stoorvogel (2000b), could solve this problem. The first results of their research are hopeful. More research is required to assess the feasibility and profitability of the combination of time and site specific management.

Conclusions

1. Nitrogen management tracks provide a useful tool for the decision support in SSM and can be assessed by the combined use of biophysical simulation and economic optimisation techniques.
2. In our case study, conditional on the validity of the WAVE simulations, site specific nitrogen management led to positive returns over variable costs compared to uniform N-application. The extra net returns were 8 Dfl ha^{-1} and 16 Dfl ha^{-1} for winter wheat and ware potato, respectively. Assuming application to an area of 100 ha, these extra returns allow for investments up to 6,300 Dfl and 13,500 Dfl, respectively. A pollution tax or a tax on nitrogen designed to internalise pollution

costs in agricultural production raises these maximum amounts to 7,600 and 33,700 Dfl, respectively. Note that in both scenarios, additional mapping, soil sampling and labour costs were not taken into account.
3. The first requirements for practical feasibility of SSM are 'good agricultural practice' and support systems for time specific nitrogen management.

Acknowledgements

The support in WAVE simulation work by Jeroen van Alphen and Marthijn Sonneveld is gratefully acknowledged.

References

Anonymous, 1997. Book keeping instructions for the LEI-department of Agriculture 1997/1998 (in Dutch). LEI, The Hague, 600 pp.

Bergström, L., H. Johnsson, & G. Tortensson, 1991. Simulation of nitrogen dynamics using the SOILN model. *Fertiliser Research* 27: 181–188.

Bouma, J., 1997a. General reflections. In: J.V. Lake, G.R. Bock & J.A. Goode (Eds.). Precision agriculture: spatial and temporal variability of environmental quality. CIBA Foundation Symposium 210 on precision agriculture: spatial and temporal variability of environmental quality. Wiley, Chichester, pp. 231–241.

Bouma, J., 1997b. Precision agriculture: Introduction to the spatial and temporal variability of environmental quality. In: J.V. Lake, G.R. Bock & J.A. Goode (Eds.). Precision agriculture: spatial and temporal variability of environmental quality. CIBA Foundation Symposium 210 on precision agriculture: spatial and temporal variability of environmental quality. Wiley, Chichester, pp. 5–13.

Darwinkel, A. & S. Zwanepol, 1997. Growing winter wheat (in Dutch). Crop grower's handbook 76. PAV, Lelystad, 84 pp.

De Jong, J.A., 1986. Growing cereals (in Dutch). Krips Repro, Meppel, The Netherlands, 206 pp.

De Koeijer, T.J., G.A.A. Wossink & F.J.H.M. Verhees, 1998. Environmental and economic effects of spatial variability in cropping: Nitrogen fertilization and site-specific management. In: G.A.A. Wossink, G.C. van Kooten & G.H. Peters (Eds.). Economics of Agro-chemicals, an overview of use patterns, technical and institutional determinants, policies and perspectives. Ashgate, Aldershot, pp. 167–179.

Dierckx, J., C. Belmans & P. Pauwels, 1986. SWATRER, a computer package for modelling the field water balance. Reference manual. Soil and Water Engineering Laboratory, Catholic University Leuven, 114 pp.

Hickman, K.A., H.O. Hunter & J.W. Byrd, 1996. Foundations of Corporate Finance. West Publishing Company, Cincinatti OH, 566 pp.

Janssen, H., 1996. Causes of differences in chemical use between farms. Phytophthora infestans in potato (in Dutch). Publication 3.162. LEI-DLO. The Hague, The Netherlands, 54 pp.

Lowenberg-DeBoer, J. & M.D. Boehlje, 1996. Revolution, evolution, or dead-end: Economic perspectives on precision agriculture. In: P.C. Roberts, R.H. Rust & W.W. Larson (Eds.) Proceedings of the Third International Conference on Precision Agriculture, Minneapolis MN, pp. 923–944.

Lowenberg-DeBoer, J. & A. Aghib, 1997. Average returns and risk characteristics of site specific P and K management: Eastern Cornbelt on-farm-trial results. Department of Agricultural Economics Staff Paper 97–2, Purdue University, West Lafayette IN, 21 pp.

Lowenberg-DeBoer, J. & S.M. Swinton, 1997. Economics of site-specific management in agronomic crops. In: F.J. Pierce & E.J. Sadler (Eds.) The state of site specific management for agriculture. ASA-CSSA-SSSA, Madison WI, pp. 369–396.

Pannell, D.J., 1997. Introduction to practical linear programming. Wiley, New York, 333 pp.

Robert, P.C., R.H. Rust, & W.E. Larson (Eds.), 1995. Site-specific management for agricultural systems. Second International Conference, March 27-30, 1994, Minneapolis, ASA-CSSA-SSSA, Madison WI, 996 pp.

Schueller, J.K., 1996. Impediments to spatially-variable field operations. *Computers and Electronics in Agriculture* 14: 249–253.

Smit, A.B., 1996. PIEteR: a field specific bio-economic production model for decision support in sugar beet growing. PhD Thesis. Wageningen Agricultural University, Wageningen, 201 pp.

Smit, A.B., P.C. Struik & J.H. van Niejenhuis, 1995. Nitrogen effects in sugar beet growing. A module for decision support. *Netherlands Journal of Agricultural Science* 43: 391–408.

Spigt, R.M., T.L.J. Janssen & S. Zwanepol, 1997. Quantitative information on arable farming and field vegetable growing 1997/1998 (In Dutch). Publication 85. PAV, Lelystad, The Netherlands, 219 pp.

Spitters, C.J.T., H. Van Keulen & D.W.G. Van Kraalingen, 1989. A simple but universal crop growth model, SUCROS 87. In: R. Rabbinge, H. Van Laar & S. Ward (Eds.). Simulation and systems management in crop protection. PUDOC, Wageningen, pp. 87–98.

Stoorvogel, J.J., G.A.A. Wossink & A.B. Smit, 2001. Theoretical aspects of precision agriculture and sustainability (in prep.).

Van Alphen, B.J. & J.J. Stoorvogel, 2000a. A functional approach to soil charaterization in support of precision agriculture. *Soil Science Society of America Journal* 64: 1706–1712.

Van Alphen B.J. & J.J. Stoorvogel, 2000b. A methodology for precision nitrogen fertilization in high input farming systems. Precision Agriculture (In press).

Vanclooster, M., P. Viane, J. Diels & K. Christiaens, 1994. WAVE, a mathematical model for simulating water and agrochemicals in the soil and vadose environment. Reference and users manual. Institute for Land and Water Management, Leuven, 154 pp.

Van Loon, C.D., A. Veerman & C.B. Bus, 1993. Growing ware potatoes (in Dutch). Crop grower's handbook 57. IKC-AGV/PAGV, Lelystad, 142 pp.

Van Wijk, A.L.M. & J. Buitendijk, 1988. A method to predict workability of arable soils and its influence on crop yield. Supplement 11. CATENA, Braunschweig, pp. 129–140.

Verhagen, A., 1997. Spatial soil variability as a guiding principle in nitrogen management. PhD Thesis. Wageningen Agricultural University, Wageningen, 109 pp.

Verhoeven, J.T.W., G.A.A. Wossink & J.A.W.A. Reus, 1995. An environmental yardstick in farm economic modelling of future pesticide use: the case of arable farming. *Netherlands Journal of Agricultural Science* 42: 331–341.

Wagenet, R.J. & J. Hutson, 1989. LEACHM, a process-based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Centre for Environmental Research, Cornell University, Ithaca, NY, 147 pp.

Wossink, G.A.A. & W.A.H. Rossing, 1998. On increasing returns and discrete choice: integrating production ecological principles in economic analysis of crop management. *Journal of Environmental Management* 54: 233–247.