AGRICULTURAL SYSTEMS

Agricultural Systems 70 (2001) 445–476

www.elsevier.com/locate/agsy

Tools for optimizing management of spatially-variable fields

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Accepted 30 March 2001

Abstract

Efficient use of agro-chemicals is beneficial for farmers as well as for the environment. Spatial and temporal optimization of farm management will increase productivity or reduce the amount of agro-chemicals. This type of management is referred to as Precision Agriculture. Traditional management implicitly considers any field to be a homogeneous unit for management: fertilization, tillage and crop protection measures, for example, are not varied within a single field. The question for management is *what to do when*. Because of the variability within the field, this implies inefficient use of resources. Precision agriculture defines different management practices to be applied within single, variable fields, potentially reducing costs and limiting adverse environmental side effects. The question is not only *what* and *when* but also *where*. Many tools for management and analysis of spatial variable fields have been developed. In this paper, tools for managing spatial variability are demonstrated in combination with tools to optimize management in environmental and economic terms. The tools are illustrated on five case studies ranging from (1) a low technology approach using participatory mapping to derive fertilizer recommendations for resource-poor farmers in Embu, Kenya, (2) an example of backward modelling to analyze fertilizer applications and restrict nitrogen losses to the groundwater in the Wieringermeer in The Netherlands, (3) a low-tech approach of precision agriculture, developed for a banana plantation in Costa Rica to achieve higher input use efficiency and insight in spatial and temporal variation, (4) a high-tech, forward modelling approach to derive fertilizer recommendations for management units in Zuidland in The Netherlands, and (5) a high-tech, backward modelling approach to detect

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PII: S0308-521X(01)00055-5

the relative effects of several stress factors on soybean yield.

Keywords: Precision agriculture; Management; Modelling; Prediction; Spatial variability; Temporal variability

1. General introduction

Efficient use of agro-chemicals is beneficial for farmers as well as for the environment. Spatial and temporal optimization of farm management will increase productivity or reduce the amount of agro-chemicals used and it can reduce leaching risks towards groundwater or water conducting acquifers.

An increasing number of tools for the analysis and optimization of management of spatial variable fields has been developed over recent years. Although general methodological aspects and applications are being published in scientific journals and being presented at conferences, the ins and outs of the tools remain hidden while little attention is paid to the underlying assumptions and rationale or on operational aspects such as data availability and data reliability.

Managing spatial variable fields (precision agriculture) is attractive and appeals instantly since large differences in crop yield are observed within farmer's fields. Traditional management implicitly considers any field to be a homogeneous unit for management: fertilization, tillage and crop protection measures, for example, are not varied within a single field. The question for traditional management is *what* to do *when*. However, for precision agriculture spatial variability needs to be included. The question is, therefore not only *what* and *when* but also *where*. To avoid ambiguities, we will adopt the following definition of precision agriculture (Bouma, 1997):

> Precision agriculture is a form of agriculture in which management is governed by variation in space and time of crop and soil conditions during the growing season within farmers' fields. The objective is to obtain high production of high quality without exceeding threshold values of environmental indicators. Precision agriculture can use advanced equipment and information technology but also applies in a low-tech context.

When reviewing current literature on precision farming, some aspects become obvious:

1. Experiments most often have a *backward-looking* character: experiments are done under well-known environmental conditions and analyzed afterwards. Weather conditions are a given fact or are influenced by man-made modifications, such as irrigation. To be of use to a farmer, tools for managing spatial variability should be able to deal with constantly changing weather, crop and soil conditions. Such a predictive decision support system is referred to as *forward-looking* (Bouma, 1997).

2. Attention is only being paid in literature to high-tech agriculture in developed countries. However, principles of precision agriculture apply as well to resource-poor conditions in developing countries. Even without high-tech options for precision agriculture, management can still be adjusted with simpler means (e.g. Bouma, 1997).

When developing decision support systems for precision agriculture that can handle the above-mentioned aspects different questions need to be answered. The question *what* should be done *when* and *where* in terms of land and crop management to realize a sustainable agricultural production system should be in balance with aspects such as: farm size and structure, technology level, economical strength and environmental thresholds. These different questions require different analysis procedures and tools.

A diagram, introduced by Hoosbeek and Bryant (1992), has been helpful to illustrate various research procedures in systems analyses studies (Fig. 1). They considered two perpendicular axes, one ranging from qualitative to quantitative and the other from empirical to mechanistic. The vertical (z) axis represents the scale hierarchy, where the pedon level (the individual soil) occupies the central position (i-level). Higher levels are indicated as $i+$, while lower levels are $i-$. The scale in Fig. 1 ranges from molecular interaction ($i-4$) to the world level ($i+6$). Different research approaches occur within the x–y plane:

K1:application of user expertise;
K2: expert knowledge;
K3: use of simple comprehensive methods, including modelling;

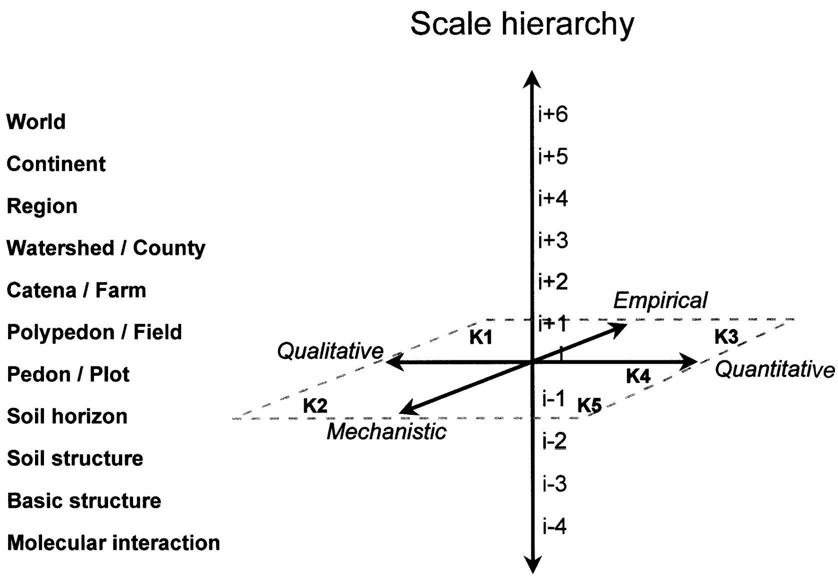

Fig. 1. Different knowledge levels in systems analysis (Hoosbeek and Bryant, 1992).

K4: complex, mechanistic methods, including modelling; and
K5: detailed methods, including modelling, which focus on one aspect only, often with a disciplinary character.

In this paper, four different case studies dealing with management of spatial and temporal variability using different research approaches will be discussed. Spatial analysis as well as modelling methodologies, varying from the application of user-knowledge to complex simulation modelling and from low- to high-tech approaches, will be classified using the Hoosbeek and Bryant scale-hierarchy (Fig. 1). In summary the cases are:

Case I: a low-tech approach using participatory mapping to derive fertilizer recommendations for resource poor farmers in Embu, Kenya. In terms of Fig. 1 this case study can be described as a K1–K2 approach on a farm scale.
Case II: an example of backward modelling to analyze fertilizer applications and restrict nitrogen losses to the groundwater in the Wieringermeer in The Netherlands. The knowledge-level of this case study is K3 applied on a field scale.
Case III: a low-tech approach of precision agriculture developed for a banana plantation in Costa Rica to achieve higher input use efficiency and insight in spatial and temporal variation. Knowledge level of this case is K2 with some aspects of K3 applied at a farm level.
Case IV: a high-tech, forward modelling approach to derive fertilizer recommendations for management units in Zuidland in The Netherlands. Due to the use of advanced simulation and spatial analysis tools this case can be regarded as a K5-level approach on a field scale.
Case V: a high-tech, backward modelling approach to determine the relative effects of several interactive stresses on soybean yield variability. A crop model is calibrated to mimic historical yield variability, and used to estimate the yield benefit if water stress, weeds and soybean cyst nematodes are eliminated (or managed) in the field. As this study is carried out using advanced simulation models it can also be regarded as a K5-level approach on field scale.

2. Case I: Embu, Kenya

2.1. Introduction

Irrespective of the specific agro-ecological conditions spatial variation in soils can be found. New high-tech solutions are being developed that enable large highly mechanized farms to manage the spatial and temporal variability. However, this does not mean that resource poor farmers under tropical conditions do not experience spatial variability. There are two major constraints:

1. traditional surveying techniques at the regional level do not provide insight in the variability at the farm level; and

2. in few cases do past experiments allow for the translation of specific conditions to the appropriate recommendations for, e.g. fertilization.

Since regional surveys do not provide the required data and detailed surveys demand resources that are typically not available, we have to look for alternative procedures. Stoorvogel et al. (2000) developed a participatory procedure to quantify the spatial variability in soil nutrient stocks. The study aimed at creating a basis for farmers to carry out site-specific management and to quantify the importance of the variation in soil nutrient stocks.

2.2. Site description

The study was carried out on the slopes of Mount Kenya in the Embu district in Kenya. Embu district shows the typical agro-ecological profile of the windward side of Mount Kenya, from the cold, wet upper zones to the hot, dry, lower zones in the Tana River Basin. The elevation ranges from 760 to 2070 m a.s.l. and average rainfall increases with altitude from 640 to 2000 mm $year^{-1}$. During previous studies five agro-ecological zones (AEZ) are identified in the district (Fig. 2). Land use in the area varies from livestock and annual crops in the lower zones to coffee, tea and dairy in the higher parts. Geologically, there is a distinct difference between AEZ 1–4 comprising basic and ultra-basic igneous rocks (basalts) and AEZ 5 comprising basement system rocks (predominantly gneisses).

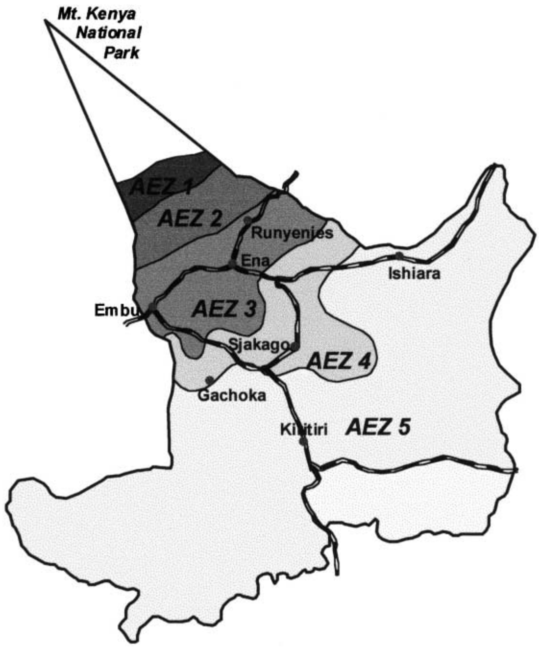

Fig. 2. Locations of the agro-ecological zones in the Embu district.

2.3. Methodology

Munyi et al. (1995) carried out a participatory rural appraisal to qualitatively describe the various agro-ecological zones, identify the major agronomic problems, and to form the basis for the farm selection. In each of the agro-ecological zones three farms were selected. The methodology to describe the spatial variability in soil nutrient stocks includes the following steps:

1. participatory mapping;
2. studying soil variability in a transect;
3. sampling; and
4. data analysis.

A participatory soil map was drawn for the farm in discussion with the farmer. It was explained to the farmer that we would like to get his perception on differences in soil fertility within his farm. The advantage of this procedure is that it yields units that are recognized by the farmer as being important. In a second step, a transect was studied throughout the farm to check whether differences identified by the farmer correspond with differences in macro-morphological characteristics of the soil. During the transect different soil horizons were identified. On the basis of the map drawn by the farmer and the results of the transect a sampling strategy was defined. Nine samples of each important soil horizon were taken and subsequently pooled to three composite samples. For very small units a single sample was taken. If a trend in soil variation was suspected (for example along a slope) the different composite samples were taken in such a way that the trend could be identified from the samples. A total of 270 samples were taken within the 15 sites. Finally the variation in soil nutrient stocks at the different farms was determined.

2.4. Results

Table 1 shows the average soil properties in the different agro-ecological zones. Clear trends can be observed. Organic matter contents increase with altitude. AEZ 5 comprises dissected erosional plains with basement system rocks (predominantly

Table 1
Average nutrient concentrations in the different agro-ecological zones (AEZ)

AEZ	pH	N_{tot} (%)	P_{tot} (ppm)	C_{tot} (%)	P_{olsen} (ppm)	K (meq/100 g)
1	4.42	0.75	2211	3.25	3.48	0.46
2	4.48	0.64	2095	2.48	2.88	1.14
3	4.53	0.44	1898	2.29	2.33	1.05
4	5.76	0.21	802	1.67	4.05	1.28
5	5.36	0.09	2237	0.65	11.22	0.48

gneisses) which have a relatively high phosphorus content compared with the basic and ultra-basic igneous rocks (basalts) found in AEZ 1–4.

The variation presented in Table 1 is the variation that can also be derived from regular soil survey. In Table 2, the average nutrient concentrations are presented for the different farms. The variation among the different farms is significant and leads to the conclusion that general fertilizer recommendations at the district level are not very useful. It should also be noted that, in general, soil surveys present chemical characteristics of the soils on the basis of one or more soil profiles. Given the variation observed between the different farms it is unlikely that the few samples taken for a regular soil survey are a solid basis for fertilizer recommendations. This is especially true if we look at on-farm variations described in Table 3. Even within farms, significant variability occurs between the different units as the farmer identifies them. The units describe a significant part of the variability that occurs within the farm. Nevertheless, even within the units significant variability does occur.

Table 2
Average nutrient contents for the different farms in Embu district

AEZ	Farm	Area (ha)	pH	N_{tot} (%)	P_{tot} (ppm)	C_{tot} (%)	P_{olsen} (ppm)	K (meq/100 g)
1	1	7.51	4.09	0.92	1998	3.94	4.85	0.54
	2	6.84	4.25	0.72	2429	2.82	2.42	0.29
	3	10.23	4.91	0.62	2207	2.99	3.18	0.53
2	4	8.89	4.62	0.55	2030	2.48	4.48	0.91
	5	7.01	4.23	0.71	2256	2.31	1.32	0.58
	6	13.81	4.59	0.65	1998	2.65	2.84	1.93
3	7	8.00	4.26	0.38	2122	2.28	3.18	1.93
	8	10.30	4.44	0.48	1876	2.56	1.85	0.39
	9	23.47	4.88	0.46	1696	2.04	1.95	0.82
4	10	14.87	5.52	0.22	1035	1.78	1.94	1.68
	11	14.82	5.99	0.19	568	1.57	6.16	0.87
5	13	25.32	6.35	0.07	51	0.77	6.25	0.52
	14	22.85	4.52	0.09	3990	0.55	11.28	0.30
	15	8.25	5.21	0.11	2669	0.64	16.14	0.62

Table 3
Average coefficients of variance (CV) for the major soil properties

AEZ	CV for properties within units (%)					CV for properties between units (%)				
	pH	N_{tot}	P_{tot}	C_{tot}	K	pH	N_{tot}	P_{tot}	C_{tot}	K
1	8	25	9	13	56	11	20	11	11	55
2	9	10	8	16	92	11	13	7	19	65
3	6	8	9	15	61	14	31	13	17	80
4	4	9	12	13	56	4	10	20	15	25
5	2	22	12	17	79	52	46	101	49	83

2.5. Conclusions

On-farm soil variation was found to be significant but at the same time highly variable between agro-ecological zones. This has severe implications for management recommendations by, for example, an extension service. The study formed the basis for a detailed analysis of soil nutrient balances that showed a similar variation partially as a result of the variation in soil fertility. Management recommendations to reduce mining of soil nutrients had to be made on a site-specific basis. Farmers were found to be aware of the differences in soil fertility and as a result it may not be necessary to carry out detailed quantitative surveys to initiate site specific management in the future.

3. Case II: Van Bemmelenhoeve, The Netherlands

3.1. Introduction

Soil spatial variability often results in variable yield patterns within fields. Verhagen et al. (1995) showed that this soil spatial variability resulted in potato yield differences within a single field of 30–45 t ha^{-1} in The Netherlands. Soil spatial variability may also lead to variable leaching patterns as demonstrated by Dagan and Bresler (1983). Finke and Stein (1994) quantified variable leaching patterns using disjunctive co-kriging and expressed leaching risks in terms of probabilities of exceeding critical levels instead of absolute values.

Simulation models are necessary in combination with geostatistics and geographical information systems (GIS) to analyze and store spatial information for precision agriculture applications. Geostatistical approaches are preferred here since they allow the analysis of small-scale field variability and they can easily handle yearly variations in patterns.

The objective of this study was to compare current, conventional farm management with site-specific management through simulation studies. Environmental and economical results were also used to judge farm management strategies. Analysis of farm management strategies was performed after the growing season had finished. Specific goals of this backward-looking scenario analyses were:

1. to define optimum time windows and amounts for nitrogen application;
2. to analyse and optimize crop yields; and
3. to minimize nitrogen losses.

Developed alternative scenarios were compared with actual field management in the same year (1994).

3.2. Site description

At the Van Bemmelenhoeve experimental farm in the Wieringermeer, The Netherlands, a field of approximately 6 ha was selected. A soil survey was conducted and the soil was classified as a Typic Udifluvent (Soil Survey Staff, 1975). Georeferenced data of the 65 soil profile descriptions within the experimental field were stored in a data base and generalized using functional horizons. Basic soil physical and chemical data for each of the functional layers was used for simulation modelling on each of the 65 points. Crop characteristics such as Leaf Area Index (LAI) and harvest data were collected at the same points throughout the growing season in 1994 (Booltink and Verhagen, 1998).

Fertilizer amounts in The Netherlands are based on the Dutch fertilizer recommendation, which uses total mineral nitrogen (N_{min}) in the rootable zone of the soil, in early spring, as a reference. The parameters for this fertilizer recommendation were derived from national trials. At the experiment described here the N_{min} level in early spring was 35 kg N ha^{-1}, which resulted in a fertilizer recommendation for spring barley of 140 kg N ha^{-1} applied in two split applications. According to the actual field management in 1994, 80 kg N ha^{-1} was applied on February 18 (day 49) and 60 kg N ha^{-1} on May 18 (day 138). Sowing of barley was on March 27 and harvest on August 12 (days 86 and 224, respectively).

3.3. Model application

To comprehend all aspects of precision farming at the field scale and to understand the output of simulation models, a systems approach is necessary. One such system is DSSAT version 3.5, Decision Support System for Agrotechnology Transfer (Jones, 1993; Uehara and Tsuji, 1993). DSSAT 3.5 was extended to use geostatistics to derive maps of simulation results based on simulated data for individual points (Booltink and Verhagen, 1998). Using this approach, year to year patterns in crop responses can be quantified in terms of semivariograms and correlation lengths. A full description of the spatial analysis software can be found in Thornton et al. (1999).

Within DSSAT, barley growth and production as well as nitrogen transport and transformation processes were simulated with CERES-Barley. A detailed model description can be found in Ritchie (1986), Jones and Ritchie (1990) and Godwin and Jones (1991).

The simulation procedure in this study is described in detail by Booltink and Verhagen (1998) and consists of basically four steps:

1. The current conventional farm management for barley was simulated for 1994 for each of the 65 profiles within the experimental field. Fertilizer was applied uniformly according to the field-averaged standard Dutch fertilizer recommendation (see earlier).
2. Based on the results of this step, a limited number of characteristic soil profiles were selected for further analysis and explorative simulation exercises (1 year, 1994).
3. Most relevant and realistic scenarios for site-specific management were selected from step 2; and used in a study in which each option was simulated for 10 years of weather data. Apart from the environmental criteria expressed as the

leaching probability of exceeding the critical 50 g m^{-3} nitrate concentration tot the groundwater, the scenarios were also judged on their economical merits.

4. Finally, the optimal scenarios were site-specifically simulated for all of the 65 profiles within the experimental field with data from 1994, and results were compared to the initial simulations of conventional farming (step 1).

3.4. Results

3.4.1. Step 1: simulation and spatial interpolation of non-site-specific management

In this first simulation step, current non-site-specific farm management was simulated. For each of the 65 profiles the field average fertilizer recommendation of 80 kg N ha^{-1}, as a first application, and an additional 60 kg N ha^{-1}, in the middle of the growing season, was applied to the entire field. Simulation results for barley seed yield and the amount of N leached to the groundwater, both expresses in kg ha^{-1}, were geostatistically analyzed. Maps for simulated barley seed yield (kriging) and the probability of exceeding the critical N leaching level of 50 g m^{-3} to the groundwater (disjunctive kriging) were created. The N leaching level of 50 g m^{-3} is in The Netherlands, on average, equivalent to 33 kg N leaching loss per ha per year. In Fig. 3, a map of simulated barley yield is presented. Yields vary from approximately 5500 kg ha^{-1} in the left (sandy) part of the field to 8000 kg ha^{-1} on the right (clayey) part. A probability map of exceeding the N leaching threshold value of 50 g m^{-3} is shown in Fig. 4. Leaching probabilities vary from 0.6 to 1.0 in the sandy part, and from 0.0 to 0.4 in the clayey part. Two representative profiles, from the clayey and sandy area, respectively, were selected for further analysis in the second step, i.e. the site-specific scenario exploration.

3.4.2. Step 2: site-specific scenario exploration

The result from this explorative simulation procedure showed that application on February 18 (day 49), 37 days prior to barley seeding, was far too early. Ten days

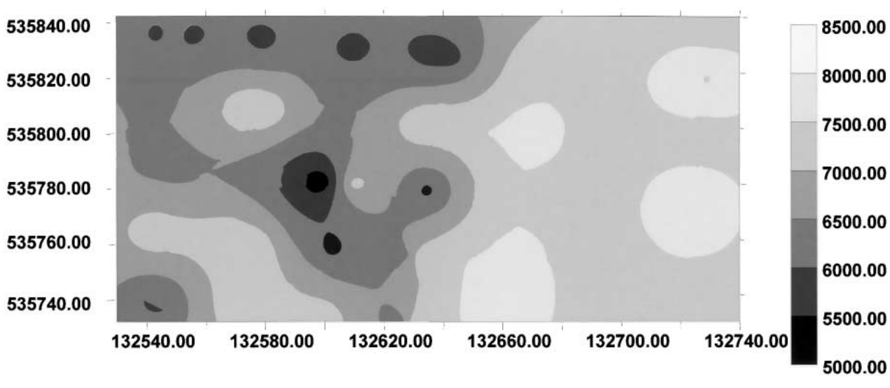

Fig. 3. Kriged map showing the 1994 simulated barley seed weight in kg ha^{-1} for non-site-specific farm management. The *X*- and *Y*- co-ordinates refer to the Dutch national co-ordinate system (RDM).

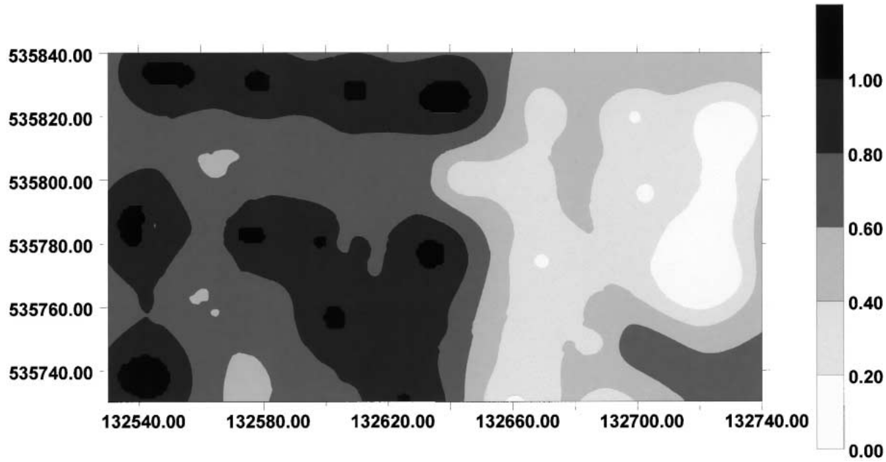

Fig. 4. Leaching maps of simulated nitrogen leaching concentrations in 1994, expressed as the probability of exceeding the critical level of 50 g nitrate m^{-3} in the leachate for non-site-specific farm management. The *X*- and *Y*- co-ordinates refer to the Dutch national co-ordinate system (RDM).

before barley seeding on March 27, there was a more efficient use of the fertilizer applied for both soil profiles.

For the sandy profile there were significant improvements. Seed weight increased from approximately 5500to more than 7500 kg ha^{-1}. The differences among the alternative scenarios were little; indicating that optimizing the time window of application is more important than increasing the amount of fertilizer applied. With respect to N leaching, the alternative scenarios perform a little better than the original simulation, however, the total amount of N leached is still far too high relative to the critical level of 33 kg N ha^{-1} $year^{-1}$. Most leaching occurred before to the start of the growing season (sowing was on March 27, day 86) indicating that the effect of limiting the amount of fertilizer applied was limited. Additional management measures are necessary to fulfil the leaching objective within this soil type.

3.4.3. Step 3: stochastically testing of site-specific scenarios

For a more reliable conclusion on the effect of alternative, site-specific scenarios the scenarios need to be tested on sets of weather data from different years to include temporal variability of weather data. Every simulation scenario for the clayey and the sandy soil profile was carried out for 10 years of weather data, resulting in a distributed model outcome (Table 4). For the clayey profile simulated barley seed weights were always higher than for the sandy profile. However, differences between the base scenario (80–49 60–138) and the alternative scenarios are larger for the sandy profile, indicating a better possibility for site-specific management on the sandy profiles within the field. The sandy profile also has a higher standard deviation of simulated seed weight, which demonstrates the higher production risks

Table 4
Simulation results for the site-specific scenarios using 10 years weather data for the clayey and sandy profiles

Scenario[a]	Seed weight ($kg\ ha^{-1}$)		N-leaching ($kg\ ha^{-1}$)		Economic return ($Dfl^{d}\ ha^{-1}$)
	Avg[b]	S.D.[c]	Avg	S.D.	
Clayey profile					
80–49 60–138	7645	1588	43.4	6.5	0
80–76 40–100	7645	1286	41.9	5.1	58
80–76 60–100	7799	1312	41.9	5.1	92
80–76 80–100	7885	1345	41.9	5.1	124
80–76 60–100 40–138	7900	1332	41.9	5.1	48
Irrigated 80–76 60–100	8033	1283	41.9	5.1	50
Sandy profile					
80–49 60–138	8340	979	19.3	6.5	0
80–76 40–100	8442	1040	19.0	6.2	67
80–76 60–100	8525	1035	19.0	6.2	92
80–76 80–100	8531	1035	19.0	6.2	83
80–76 60–100 40–138	8553	1021	19.0	6.2	61
Irrigated 80–76 60–100	8626	902	19.0	6.2	24

[a] Scenario codes refer to the day number and amount of fertilizer applied on that date, e.g. 80–49 60–138 refers to a split application of 80 and 60 kg N on days 49 and 138, respectively. Irrigated refers to a scenario in which a single irrigation of 25 mm was applied. Economic return is relative compared to the base scenario (80–49 60–138)

[b] Avg, average simulated value.

[c] S.D., standard deviation.

[d] Dfl, Dutch guilder.

on this type of soils. Since most of the leaching occurs prior to the growing season, as previously mentioned, differences in the amount of N leached did not vary much between the base and alternative scenarios. One can conclude that in the clayey profile the critical leaching concentration of 50 g m^{-3} (equivalent with 33 kg N ha^{-1} $year^{-1}$) will not be exceeded with a probability of more than 95%. On the sandy profile, on the contrary, the critical level is always exceeded.

The relative economic return (1 Dfl≅0.5 US dollar) is calculated with the 80–49 60–138 scenario as base level. The margins on the sandy soil are higher, ranging from 58–124 Dfl, compared with 67–92 on the clayey profile. The most economically profitable scenario for the clayey soil is scenario 80–76 60–100, and for the sandy profile scenario 80–76 80–100. The triple fertilizer applications (80–76 60–100 40–138) result in slightly higher yields for both profiles but the costs of an additional application does not result in extra economic returns. The last scenario (irrigated 80–76 60–100) refers to a scenario in which one single irrigation of 25 mm was applied during the dry period in early July. This scenario results in higher yields for both profiles, but the costs of an irrigation application were not recovered by the extra return of a higher yield. Irrigation does, however, reduce the management risk as indicated by a lower standard deviation of the simulated seed weights.

3.4.4. Step 4: simulation and interpolation of optimized management scenarios

Based on the individual soil profile description of each of the 65 soil profiles, the soil profiles were grouped into either a *clayey* or a *sandy* category. The most economically profitable scenarios for both profiles, as obtained in the previous step, were used in site-specific simulation for the experimental field using the actual weather data from 1994. Simulation results were geostatistically analyzed and maps of yield and nitrogen leaching were produced (Figs. 5 and 6). Compared with the original, non-site-specific, scenario (Figs. 3 and 4), site-specific application results in a higher yield for the experimental field. Yields for the site-specific simulation range from 7000 to 8500 kg ha^{-1}, compared with 5500–8000 kg ha^{-1} for the non-site-specific simulation. For N leaching the site-specific simulation results in low-leaching probabilities in the clayey part (lower than 0.20). For the sandy part of the experimental field leaching probabilities are, due to the fact that most leaching occurs prior to the growing season. Only additional management practices that reduce post-harvest N content in the soil or retain N, such as catch crops, can prevent excessive leaching on these sandy profiles.

3.5. Conclusions

This case study shows that simulation models are powerful tools to fine-tune fertilizer amounts and dates, providing benefits to both the farmer and the environment. Simulated economic benefits of this site-specific approach are low, especially when realizing that costs to implement site-specific management are not included. However, knowing the small financial margins on cereal crops within the European Community, it can already be a significant amount.

Learning and analyzing former management practices was the main goal of this backward-looking modelling approach. For analysis of ongoing management in the current growing season a forward-looking approach is required (Case IV).

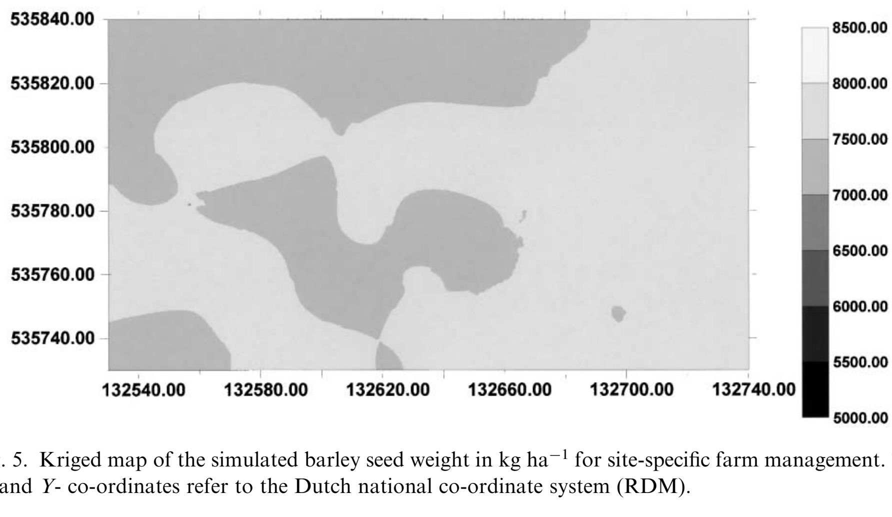

Fig. 5. Kriged map of the simulated barley seed weight in kg ha^{-1} for site-specific farm management. The *X*- and *Y*- co-ordinates refer to the Dutch national co-ordinate system (RDM).

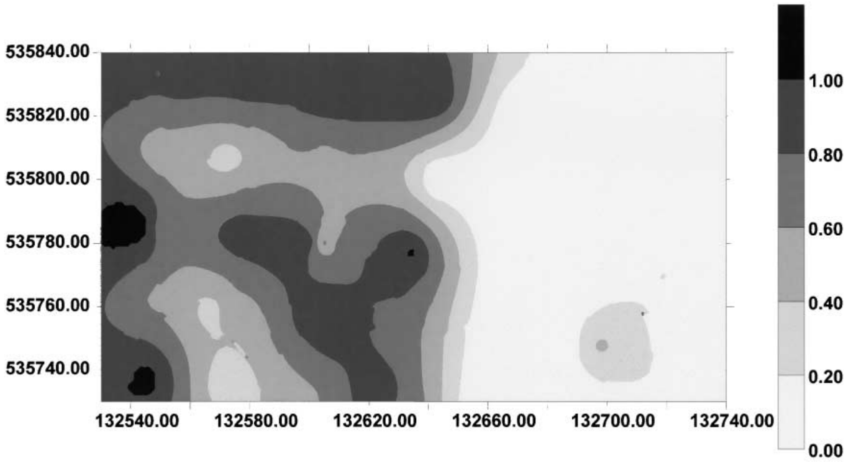

Fig. 6. Leaching maps of simulated nitrogen leaching concentrations, expressed as the probability of exceeding the critical level of 50 g nitrate m^{-3} in the leachate for site-specific farm management. The *X*- and *Y*- co-ordinates refer to the Dutch national co-ordinate system (RDM).

4. Case III: Rebusca plantation, Costa Rica

4.1. Introduction

This section presents a methodology for a low-tech approach to precision agriculture that has been developed for a banana plantation in Costa Rica. Banana plantations in Costa Rica have to deal with decreasing economic returns and at the same time are pressured to increase input use efficiency. In precision agriculture many techniques are used that are not applicable to the very specific management system of bananas: harvesting occurs on a weekly basis, machinery is almost absent since the system relies almost entirely on manual labour, and crop growth simulation models are not available. Nevertheless, there is an increasing call for the development of alternative management practices that decrease external inputs and make the production system more efficient. Information and communication technology allows us to quantify the spatial and temporal variation in crop performance and link that to soil information. It can be expected that farm managers will be able to achieve higher input use efficiency if they have insight in this spatial and temporal variation.

To enable farm management to apply the principles of precision agriculture as described earlier, a database management system was be developed that takes care of the registration of soil and production data. Given the spatial character of most data it is logical to build a decision support system around a GIS. User-friendliness is a first requisite for the decision support system. The system should enable farm managers to consult the soil map, to generate yield maps and, finally, to identify problem areas. In a second phase, the system should be able to store management operations and enable farmers to retrieve past management (as a possible cause for problem areas). This type of alternative management system can only being implemented on farms if the proper institutional structure is present. Soil surveys, digitization of information, and the interpretation of complex data sets requires specific knowledge that is not likely to be present at a banana plantation, nor is specific computer hardware and software. Therefore, it is proposed that a decision support system is strongly supported by an institution (e.g. an extension service or, for the specific Costa Rican case, the National Banana Growers Corporation (CORBANA). The institution can take care of the soil survey, digitalization of information and backstopping. The farmer, in turn, interprets the information and results with his/her specific knowledge of the plantation and its crop.

4.2. Site description

The decision support system for banana management BanMan (Stoorvogel, 1998) has been developed and implemented on the Rebusca plantation. The Rebusca plantation (84°01′ E, 10°28′ N) covers an area of 107 ha and was established in 1991, during the expansion of the banana area in the Atlantic Zone of Costa Rica. A low-tech approach has been followed to deal with the development of a prototype for banana management. The current decision support system allows farm managers to quantify and analyze spatial and temporal variability of yields of the plantation. Through a consecutive analysis of the results, the system is able to identify the so-called problem areas and analyse temporal trends.

Soil variability in the plantation was described through a detailed soil survey (1:5000) with 454 borings on a 50-m grid (see Fig. 7). In contrast to traditional surveying practices, soil horizons were classified into functional horizons and not as the more traditional genetic horizons. Functional horizons consist of combinations of genetic horizons with similar behaviour, i.e. the combined horizons have similar physical and chemical properties (Finke, 1993). In this way, the spatial variability of soil properties is characterized by spatial variation in the thickness of the horizon and the intrinsic variability of the properties of each functional horizon (Finke et al., 1992). The augurings describe the location of the functional horizons in a three-dimensional space. Functional horizons were sampled in triplicate for soil chemical and physical analysis. The number of functional horizons is limited and as a result, significantly reduces the number of required analysis (compared with traditional surveying techniques).

4.3. Site-specific yield registration

A methodology for site-specific yield monitoring was developed within BanMan (Stoorvogel, 1998). Depending on weather conditions, specific locations are checked for bunches with bananas with the proper grades approximately once a week. Selected bunches are harvested and transported manually to a grid of cables traversing the plantation. When 20–30 bunches are harvested, they form a ‘train’ that is pulled to the packing plant where the bananas are processed and packed. To enable yield mapping, the area along the cable is harvested sequentially and the point where the last bunch is harvested is registered. Bunches in a particular train originate from

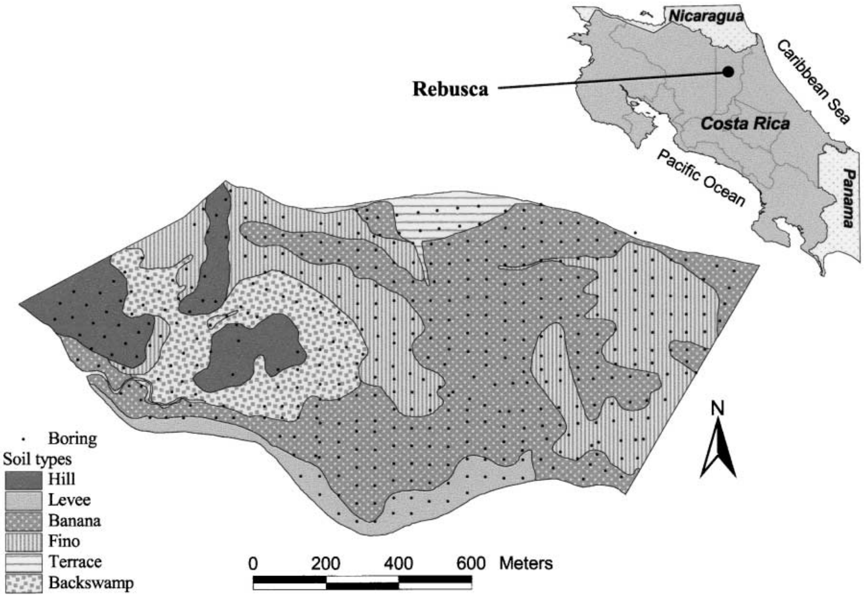

Fig. 7. Soil map of the Rebusca plantation (1:5000).

the area between the last bunch of that train and the last bunch of the previous train (or the beginning of the cable if it is the first train). A weighing device is placed in the cable where bunches enter the packing plant.

The yield units, i.e. the spatial units that supply bunches to one specific train, vary in size and location between harvests. To compare and aggregate yields of different days, it is necessary to disaggregate the data to standard 'yield registration units' (YRU).

The farm is subdivided in 450 YRUs for which yield is determined. The units vary in size between 0.1 and 0.9 ha. BanMan combines the data of all the trains entering the packing plant and disaggregates the data with respect to the YRUs. Subsequently, BanMan creates a yield map. Yield maps can be created with different temporal resolutions. In most cases, farm management works with 4-week periods and yield maps are created for the same period. Spatial resolution is of similar importance. Traditionally, yields were registered for the whole farm or per cable. Currently, measurements for yield maps are based on the YRUs. The effect of measurement scale is demonstrated in the yield maps presented in Fig. 8. Clearly, the measurements for the whole farm or per cable are too crude for site-specific management. However, the smaller management units are perhaps too detailed from a management point of view.

4.4. Spatial analysis

Yield maps in combination with soil maps enable farm management to perform better analyses of production patterns. A large part of the observed differences is

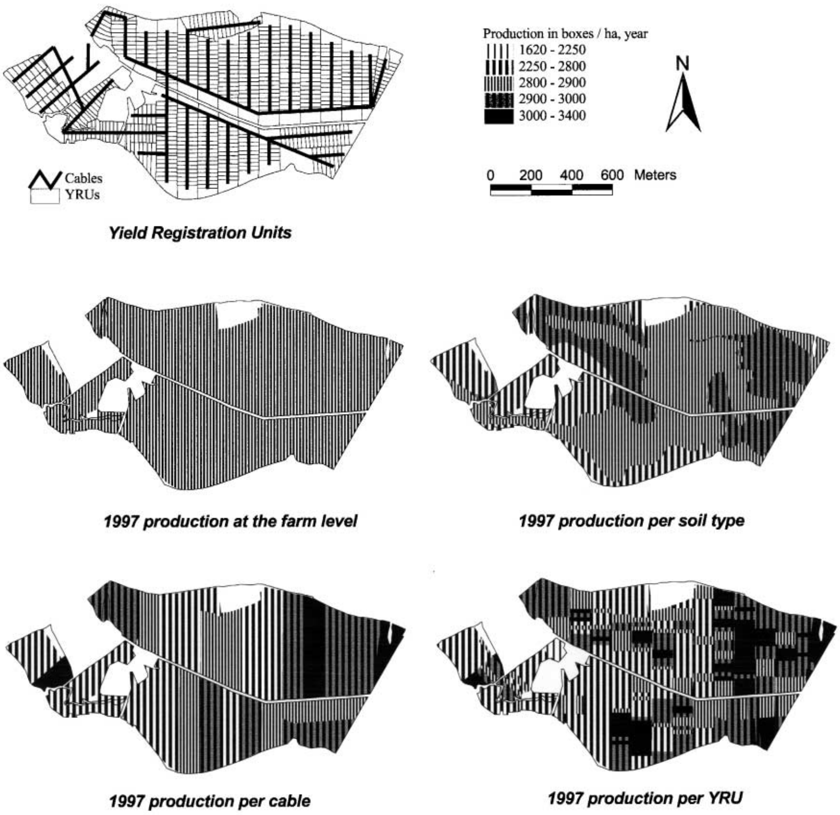

Fig. 8. Yield variation (1997) in the Rebusca plantation at four scale levels.

likely to originate from soil variability. Deviations of −30 to +32% from the mean yield within a soil unit do occur. All soil variation within soil units, however, does not necessarily result in yield variation. Part of the observed variation is probably due to pests and diseases and part to differences in management, as this is mainly based on manual labour. Deviations to the mean were classified to detect extreme situations in problem areas (Fig. 9).

Banana plantations typically apply the same level of fertilization across the entire plantation. It is likely that with variation in yields fertilizer requirements vary as well, as the amount of nutrients removed by the banana crop varies significantly with differences in yields. Yields in a problem area may be low as a result of nutrient availability and management may decide to increase fertilization for that particular area resulting in a yield increase. However, if yields are low due to pests or drainage problems, increased fertilization will not lead to increased crop growth and fertilizer will leach to the environment. As proper simulation models for the banana crop are lacking, farm managers will have to rely on their expert knowledge to determine optimal fertilizer rates. In other words, by

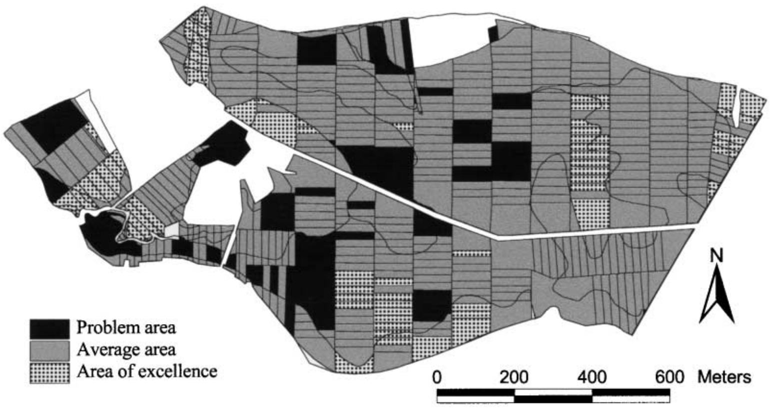

Fig. 9. Location of the problem areas in the Rebusca plantation (1997 data).

overlaying soil survey data with production maps, one filters for differences in soil type (typically static properties, which can only be changed in the long run). Other differences, i.e. differences within the soil units, are likely to be the result of planting material, diseases and/or management. Additional field observations and chemical analysis of crop and soil may be used to explain the differences. Through the identification of site-specific problems, farm management may improve these local limitations, improving the performance of the farm and at the same time reducing costs.

4.5. Conclusions

It is important to adequately define the spatial and temporal resolution with which precision agriculture will be applied. Currently, management in most cases is uniform over the plantation, except for drainage that considers the inherent drainage status of the soil. Fertilization and biocide applications are not varied over the plantation. Yields as well as plant density and some other characteristics are registered for the plantation as a whole or in some cases per cable. Given the fact that cables are positioned in such a way that there is a slight slope towards the packing plant, they typically include high soil variability. This makes interpretation of data per cable rather awkward.

Traditionally, agricultural research took place on experimental farms, after which promising results were transferred to farmers. Increasingly, research takes place in on-farms trials. Nevertheless a top-down approach is being followed in which farmer's knowledge plays a minor role. Although this type of trials will also be necessary in the future to understand specific components of the cropping system, they should be supplemented with participatory approaches. Participatory approaches assure that the alternative management systems are better adapted to the socioeconomic setting of the farm resulting in higher adoption rates.

5. Case IV: Zuidland, The Netherlands

5.1. Introduction

An interdisciplinary research team in The Netherlands is currently working on the development of a decision support system for precision agriculture. Although research is still in progress, the outline of a decision support system for precision agriculture is taking shape. Booltink et al. (1998) and Bouma et al. (1999) described the system, which is designed for arable farming and reflects Dutch conditions, in detail.

The DSS is founded on a detailed soil database containing both primary (e.g. texture, organic matter content) and secondary soil data (hydraulic characteristics) for a large number of soil auger observations. Secondary data are derived through continuous pedotransfer functions (Wösten et al., 1998).

Questions to be resolved by the decision support system may include whether fertilizer should be applied and, if so, at which locations and at which quantities? A forward-looking approach is pursued, allowing a pro-active response to the near depletion of nutrients in (part of) a field. This requires dynamic and spatially differentiated estimates of the actual supply and demand for nutrients. Estimates are provided through real-time simulations for representative soil profiles located in different soil units. The simulations quantify soil water fluxes, N-transformations and solute movement on a daily basis. In turn, these data are used to generate early warning signals for water and/or N-depletion in the root zone.

This section focuses on the development of two important DSS components:

1. the delineation of soil functional units at the field level to be used as management units for precision agriculture; and
2. the development and application of a fertilizer recommendation system based on real-time simulations for representative soil profiles.

5.2. Site description

Research was conducted at the Van Bergeijk farm in The Netherlands. The Van Bergeijk farm is a commercial arable farm of approximately 100 ha situated on Voorne-Putten; one of a series of (former) islands located in the southwestern part of The Netherlands. Soils on Voorne-Putten consist of marine deposits, are generally calcareous and have a texture ranging from fine loam to heavy clay-loam. With excellent drainage conditions, controlled by a dense system of pipe-drains, these soils are considered prime agricultural soils. Crop rotation is applied using winter wheat, consumption potato, sugar beet and summer barley as the main cultivates. A basic farm layout is presented in (Fig. 10).

During spring 1997, a detailed soil survey was conducted at the Van Bergeijk farm. Basic soil properties, including texture and soil organic matter (SOM) content, were determined for individual soil horizons at 612 soil sampling sites (Fig. 11). Sampling sites were georeferenced and hydraulic characteristics were estimated

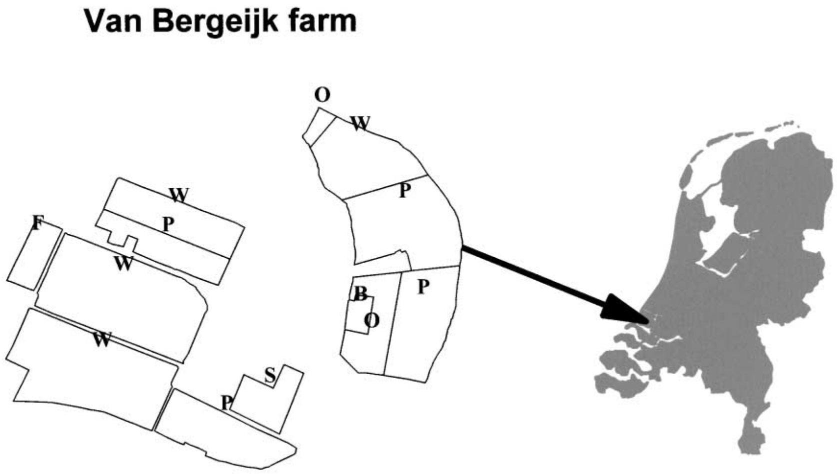

Fig. 10. Farm layout of the Van Bergeijk farm in 1997. Abbreviation p stands for potato, w for wheat, b for barley, s for sugar beets, f for fallow and o for other crops.

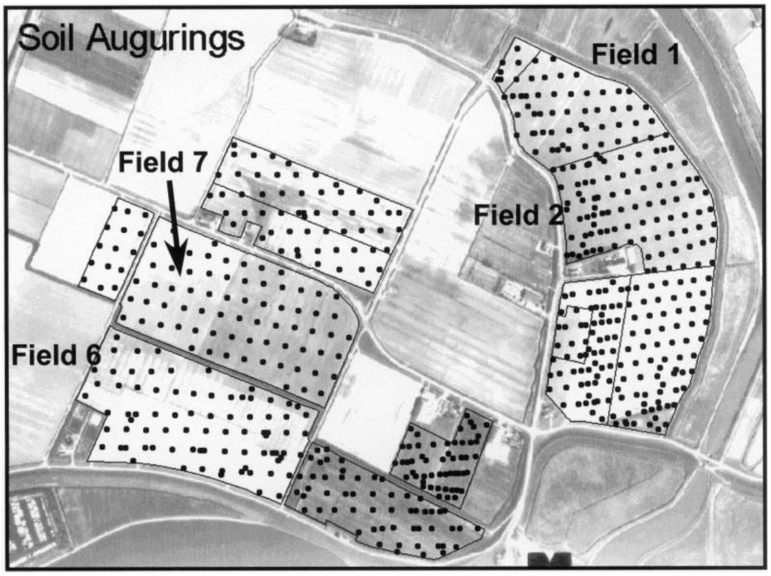

Fig. 11. Position of the 612 soil augurings on the Van Bergeijk farm.

using continuous pedotransfer functions (Wösten and Van Genuchten, 1988). Soil layers were classified into a total of 16 taxonomic classes defined by the Dutch 'Staring series' (Wösten et al., 1987). This classification distinguishes between topsoil and subsoil layers, which are further differentiated towards texture and SOM-content. Each taxonomic class was sampled in the field to determine average soil physical characteristics using the crust infiltrometer (Booltink et al., 1991) and multi-step outflow methods (Van Dam et al., 1990). Van Alphen and Booltink (2000) showed that hydraulic characteristics derived through a combination of pedotransfer estimates and simple on-site physical measurements (i.e. saturated moisture content and bulk density) gave best results when simulating soil moisture regimes in the study area.

For reasons of brevity, attention is focused on a single field covering 14.7 ha. Soil variability is mainly present through differences in texture (clay content over 0–1 m varies from 14 to 50%), SOM-content (0.5–5.8% SOM over 0–1 m) and subsoil composition (peat or mineral matter).

5.3. Simulation modelling

Dynamic simulations of soil–water–plant interaction were conducted with the mechanistic-deterministic simulation model 'WAVE' (Water and Agrochemicals in soil and Vadose Environment; Vanclooster et al., 1994). WAVE integrates four existing models describing:

1. one-dimensional soil water flow: SWATRER (Dierckx et al., 1986);
2. heat and solute transport: LEACHN (Hutson and Wagenet, 1992);
3. nitrogen cycling: SOILN (Bergström et al., 1991); and
4. crop growth: SUCROS (Spitters et al., 1989).

Differential equations governing water movement (Richards' equation) and solute transport (convection-dispersion equation) are solved with a finite difference calculation scheme. For this purpose soil profiles were divided into 1-cm compartments.

Water stress is calculated according to Feddes et al. (1978). Maximum uptake rates are defined by a sink term, which is considered constant with depth. Water uptake is reduced at high and low pressure head values, according to crop-specific thresholds. Stress resulting from N-deficiency occurs when required N-concentrations in the plant cannot be sustained by actual uptake rates. Crop production is then reduced proportionally to the ratio of actual over required uptake. A detailed description of the modelling procedures is presented by Van Alphen and Stoorvogel (2000a, 2000b).

5.4. Describing soil variability: soil functional units

Soil variability was described in terms of selected soil functional properties. These were derived for individual soil profiles (point data) using the WAVE model. Winter wheat was selected for crop growth simulation and management parameters (e.g. date and dosage of split fertilizer applications) were chosen after common practice. Four functional properties were considered:

1. water stress in a dry year;
2. N-stress in a wet year;
3. N-leaching from root zone in a wet year; and
4. residual N-content at harvest in a wet year.

The first two properties describe the sensitivity of a soil to the effects of major growth-limiting factors. These are directly related to crop production and therefore relevant from an economical perspective. Properties three and four are environmental parameters describing the pace at which nitrates are leached from the root zone.

Fuzzy c-means classification (FCM) was used to identify classes of functionally similar soil profiles in the experimental field. Several authors, e.g. Burrough (1996) and McBratney and Odeh (1997), have described FCM classification. As opposed to traditional discrete classifiers, FCM expresses class-membership on a continuous scale of 0–1. Multiple classifications were calculated using a range of 2 to 7 functional classes. Two validity measures were derived for each classification: the fuzziness performance index (F') and the normalized classification entropy (H'') (Roubens, 1982). These measures quantify a degree of 'non-fuzziness', which is maximized when F' and H'' reach their minimum value. McBratney and Moore (1985) indicate that the corresponding number of classes reflects a balance between structure and continuity that is generally pursued. Minimum values for F' and H'' were in this case attained with four functional classes. An overview of the average soil functional and soil physical properties per class is presented in Table 5.

Class-membership values of all soil profiles were interpolated using ordinary kriging (Journel and Huybregts, 1978). This required separate interpolations for each functional class resulting in multiple grid maps. These grids were combined to derive a single confusion index map (CI-map) covering the entire field (Fig. 12). In Eq. (1), the CI [0...1] is defined as: (Burrough et al., 1997).

$$\mathrm{CI} = 1 - \left(\mu_{1,i} - \mu_{2,i}\right) \tag{1}$$

in which $\mu_{1,i}$ is the highest membership value in grid cell i and $\mu_{2,i}$ is the second largest membership value in the same grid cell. In cases where CI-values approach 0, one functional class clearly dominates, leaving little confusion about class membership. Where CI-values approach unit value, two classes have similar membership values resulting in 'confusion' about class membership. On the CI-map such areas are interpreted as spatial 'transition zones' between the functional classes. They appear as light colored areas in Fig. 12, forming a clear pattern in the experimental field. Soil functional units Fig. 12 were subsequently delineated using CI > 0.9 as the threshold

Table 5
Average soil functional and soil physical properties (in parentheses standard deviations) for the four functional classes identified in the experimental field[a]

Class	Count	Water stress	N-stress	N-leaching (kg N ha^{-1})	N-residual (kg N ha^{-1})	Clay % (0–100 cm)	SOM % (0–100 cm)
1	25	0.99 (0.02)	1.00 (0.00)	29.8 (4.1)	90.1 (14.3)	41.8 (4.5)	0.9 (0.2)
2	16	0.71 (0.07)	1.00 (0.00)	37.1 (6.9)	106.3 (19.3)	46.3 (3.0)	1.8 (0.3)
3	30	0.98 (0.04)	1.00 (0.00)	36.8 (3.3)	86.9 (10.9)	30.7 (7.6)	1.2 (0.3)
4	10	0.96 (0.06)	1.00 (0.00)	56.3 (9.1)	154.5 (16.5)	33.7 (7.4)	3.1 (1.1)

[a] Count indicates the number of soil profiles grouped in each class.

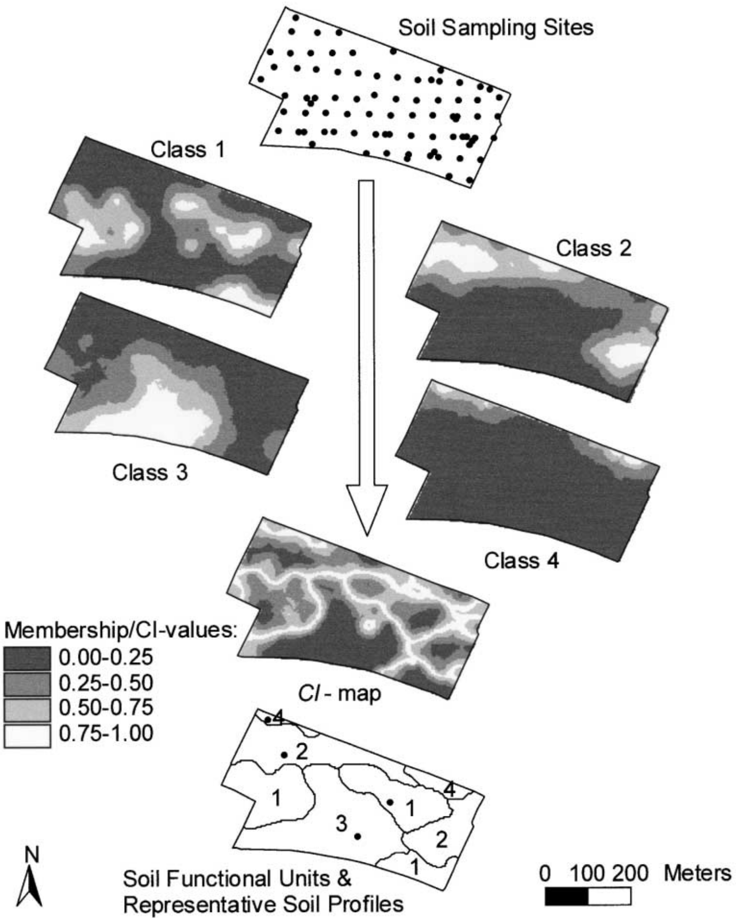

Fig. 12. Deriving management units for precision farming. The confusion index is calculated with Eq. (1). The map was derived by kriging of individual CI values on every of the soil auguring points within the four fields.

level for a boundary detection algorithm (ESRI, 1998). Each unit was assigned a representative soil profile that best matched its functional characteristics. Finally, the classification efficiency was evaluated by calculating coefficients of determination (R^2) for the underlying functional properties. R^2-values ranged from 70% (N-residual) to 86% (water stress), reflecting the large percentage of the total spatial variation accounted for by the functional units. Reference is made to Van Alphen and Stoorvogel (2000a) for further details regarding the applied methodology.

5.5. Decision support: nitrogen fertilization based on real-time simulations

An important component for the future DSS is a fertilizer recommendation system for nitrogen. The system has been developed following a participatory approach in which the farmer was regularly informed and consulted for advice. During field experiments the system proved simple and effective.

Spatial variation is accounted for by soil functional units, which are used as management units for 'precise' fertilization. Timing and amount of split fertilizer applications are optimized using real-time simulations for representative soil profiles in each unit. Climatic data required for this purpose are downloaded directly from an on-farm weather station. The simulation model calculates: (1) N-uptake rates by plants; and (2) soil-N levels in the root zone. Both are evaluated on a weekly basis. A minimum level for available soil-N is defined at twice the uptake rate over the past week. Once soil-N levels drop below this threshold, an early warning signal is generated triggering the application of additional fertilizer. Fertilizer amounts are determined in relation to plant uptake rates by calculating the approximate amount required for a period of 4 weeks. The last of a series of (usually) four split applications is applied in accordance with expected yield levels. Yield estimates are derived through simulation by extending the available weather file with historical data from a wet, a dry and a 'normal' year.

The simulation procedure described earlier can theoretically be applied to all 612 soil profiles sampled on the Van Bergeijk farm. This could result in a near continuous fertilizer recommendation map for nitrogen. The management unit concept is, however, more practical: (1) representative soil profiles vastly reduce the total required number of simulations; and (2) farm equipment is at present not suitable for continuous variation of fertilizer applications (i.e. the working width of the fertilizer spreader measured 32 m).

The described recommendation system was tested during two field experiments in 1998 (Van Alphen and Stoorvogel, 2000b) and 1999. In both cases, recommendations were provided for winter wheat and results were compared with traditional N-management. Fertilizer strategies included four split fertilizations and results showed that (1) 'precise' fertilizations were generally applied later and (2) the total amount of N-fertilizer was reduced by 13–26%. Yield levels and grain quality were found to be equal for precision and traditional management.

Table 6 summarizes results of the 1998 field experiment. Towards the end of the growing season precision management resulted in lower recommendations resulting in a 55 kg ha^{-1} reduction on fertilizer inputs. Fig. 13 presents simulated soil-N levels and weekly N uptake rates for a management unit in the experimental field. As a result of leaching during the winter season initial N concentrations were low (31 kg N ha^{-1} measured in February 1998). Fertilizer applications on days 52, 113 and 140 are indicated by steep increases of soil-N levels. N uptake varies according to crop development stage and weather conditions. After a base fertilization in February, the second and third applications were timed using a threshold level for soil-N (i.e. minimum level equal to twice the uptake rate over the past week). A scheduled fourth application was cancelled when fungus infestations were detected in the wheat crop. Note that post-harvest N levels are below 20 kg N ha^{-1}. This is important since Verhagen and Bouma (1997) indicated that levels below 35 kg N ha^{-1} are acceptable from an environmental perspective (i.e. nitrate leaching to the groundwater will not exceed the EC-drinking water directive of 50 mg l^{-1}).

Table 6
Results of the 1998 field trial in which traditional fertilizer management was compared with precision fertilization following the developed fertilizer recommendation system (Van Alphen and Stoorvogel, 2000b)

Date	Traditional ($kg\ ha^{-1}$)	Precision agriculture ($kg\ ha^{-1}$)
21 February	80	80
23 April	80	60
20 May	80	45
Total	240	185

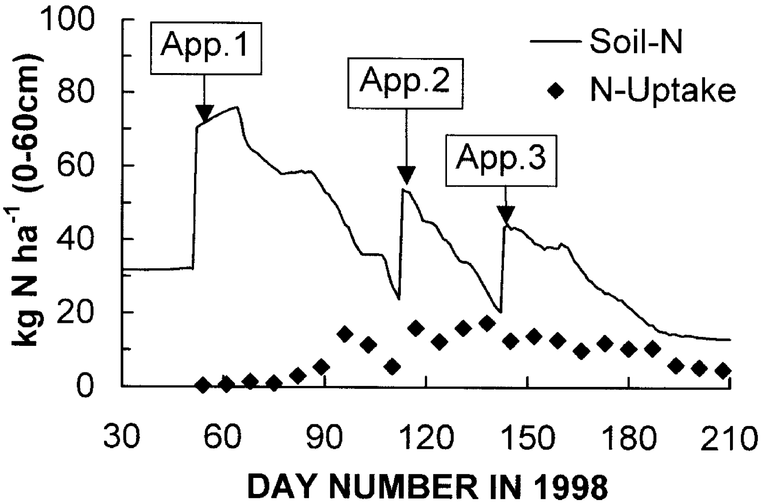

Fig. 13. Simulated soil nitrate-N level (0–60 cm) and winter wheat weekly uptake rates at the Van Bergeijk farm from 1 January 1998 until 26 July 1998.

5.6. Conclusions

Soil functional units proved efficient in describing the spatial variability of selected functional properties. Coefficients of determination always exceeded 70%, meaning that less than 30% of the total spatial variation was lost through generalization. Functional units are, therefore, considered suitable entities to be used as management units for precision agriculture.

Real-time simulations provide a powerful tool to be used in decision support systems for operational precision management. Field experiments showed that fertilizer inputs could be reduced by 13–26% without affecting crop yield and quality. In addition, fertilizer leaching could was reduced to a minimum.

Adequate and reliable parameterization is a major problem for wide range application of simulation models in precision agriculture. Newly developed methods to derive input parameters from a combination of pedotransfer functions and simple measurements (Van Alphen and Booltink, 2000) as well as through remote sensing (D'Urso and Menenti, 1995; Booltink et al., 1998) allow for reliable model application with minimum data sets.

Although simulation models have proven their validity in this study, application requires much effort in terms of data collection and the validation-calibration procedure. For flexible future applications these simulation models need to be generalized, e.g. by means of transferable regression equations based on long-term simulation modelling at pilot sites.

6. Case V: understanding causes of soybean yield variability

6.1. Introduction

Spatial yield variability is a complex interaction of many factors including water stress, rooting depth, soil and drainage properties, weather, pests, fertility, and management. The challenge for farmers is to identify the factors that they can control and manage, and make appropriate management decisions to increase profits. In the non-irrigated midwestern USA, there is much evidence that water stress is a dominant soybean yield-limiting factor. Although producers cannot control this limitation, water stress does interact with other biotic stresses that can be managed. Biotic stresses such as soybean cyst nematodes (SCN) and weeds can also create significant spatial yield variability, and can be controlled through proper management. The objective of this study was to quantify the effects of water stress, SCN, and weeds on spatial soybean yield variability.

6.2. Site description

This study was carried out on a 20-ha field near Perry, Iowa. The field has rolling topography and is in the Clarion-Nicollette-Webster soil association. The field is drained by subsurface tile lines to reduce the impact of high water tables that normally occur during the spring. For this study, the field was divided into 100 grids 0.2 ha in size. Basic soil information required for modelling (i.e. texture, bulk density, water holding capacity, hydraulic conductivity) was obtained from a detailed on-site soil survey conducted for each grid. Soybean yield data were collected in 1995, 1997 and 1999 using a yield monitor mounted on a combine. Relevant crop management (e.g. plant population, fertilizer rate) and soil information were collected as well. In addition, soybean cyst nematode (SCN) spring egg count, weed species and density data were measured for each grid.

6.3. Methodology

The CROPGRO-Soybean model (Hoogenboom et al., 1994) was used to characterize spatial yield variability in the field. The model was developed to compute growth, development, and yield on homogeneous units. This model requires inputs including management practices (variety, row spacing, plant population, fertilizer and irrigation application dates and amounts) and environmental conditions (soil type, daily maximum and minimum temperature, rainfall and solar radiation). From this information, daily growth of vegetative, reproductive, and root components are computed as a function of daily photosynthesis, growth stage, and water and nitrogen stress. Soil moisture and nitrogen balance models are used to compute water and nitrate levels in the soil as a function of rainfall and soil moisture holding properties. Because the model is process-oriented, it is relatively simple to couple additional processes such as impact of pests, to daily calculation of state variables.

A procedure was developed to calibrate the model to mimic the historical yield variability in individual grids. The procedure begins with identifying potential causes of yield variability. For this field, we identified water stress, SCN and weeds. Fertility was eliminated based on soil fertility measurements. Recently, methods have been developed to simulate the effect of SCN and weeds using the model (Fallick, 1999; Paz, 2000). Model inputs for these two pests were measured in the field. However, the model inputs related to tile drainage and water stress (potential rooting depth, tile flow rate and hydraulic conductivity of the impermeable layer) are not easily measured. Thus, the third step was to calibrate these three factors for each grid to minimize the error between predicted and measured yield over time. This analysis focused on 77 grids that had complete sets of data for the three seasons. Finally, we used the model to estimate the effects of water stress, SCN and weeds for the 1997 data set.

6.4. Results

Using this approach, the model was able to explain approximately 80% of the spatial and temporal yield variability over the 3-year period (Fig. 14). The effects of three yield-limiting factors were computed for 1997 using the calibrated model. Fig. 15 shows the predicted and measured yield for 1997 with all stresses incorporated (▲). Next, the maximum potential soybean yield was computed for each grid in 1997 by turning off all stresses (+), which was approximately 4000 kg ha^{-1}. The values vary slightly from grid to grid because of differences in measured plant population. For a specified grid, subtracting the ▲ value from the + value indicates the estimated yield loss due to the combined effects of water stress, SCN, and weeds. Next, the yield increase that would occur by eliminating water stress from each grid was predicted by turning off water stress, and leaving SCN and weed stress turned on (◇). Finally, the yield increase due to eliminating SCN (●) or weeds (□) was computed by turning each stress off separately.

The average estimated yield loss (over all grids) due to the combined effects of water stress, SCN, and weeds in each grid was 842 kg ha^{-1} (Table 7). A significant number of grids had high yield reduction of greater than 2000 kg ha^{-1}. Water stress was the most yield-limiting factor, causing an average of 626 kg ha^{-1} loss, followed by SCN (105 kg ha^{-1}) and weeds (18 kg ha^{-1}). Interestingly, the total yield loss due to all stresses was 842 kg ha^{-1}, which was more than the estimated

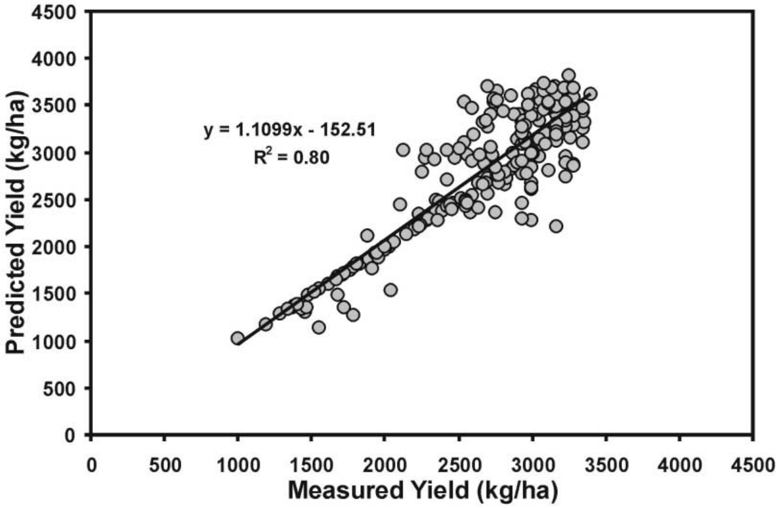

Fig. 14. Comparison of measured and predicted soybean yield for the McGarvey Field after calibrating three parameters (RHRF, FLDS, KSAT), and using 3 years of data.

yield loss attributed to each stress separately. The model estimated that a yield loss of about 93 kg ha^{-1} occurred due to interactions between water stress, weeds and SCN.

6.5. Conclusions

Information on soil SCN and weed population allowed us to identify causes of yield variability other than water stress, and the degree at which these factors may have affected model prediction. The technique presented in this study shows the value of using a crop growth model in quantifying the individual as well as combined effects of yield variability factors.

7. Future needs and opportunities

The technical development of decision support systems for precision agriculture has reached a stage in which the systems can be applied under practical conditions. Researchers, in close interaction with farmers, have a responsibility now to 'package' their information in a form allowing farmers and decision makers to make decisions as to using these systems. The interaction of different users, as well as disciplines, will allow the development of well-balanced multidisciplinary tools, avoiding the trap in which mono-disciplinary tools are developed that claim to be the solution for all problems. To allow proper judgement of the results, these decision support systems need to be transparent in use and structure and well documented. Such an open system will allow the addition of other future routines such as the

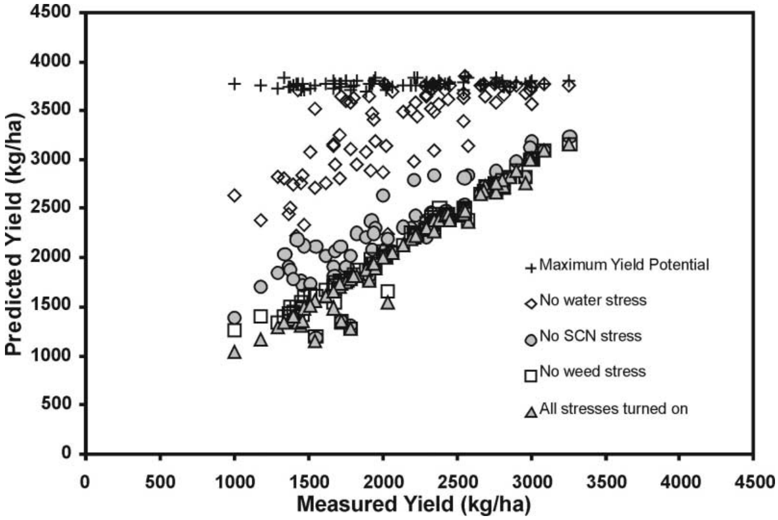

Fig. 15. Maximum potential soybean yield in 1997 and variations in predicted soybean yield as affected by SCN, weeds, and water stress.

Table 7
Average estimated soybean yield losses in 1997 due to the effects of water stress, SCN, soil pH, and weeds

Yield reduction factors	Yield loss (kg ha^{-1})
Water stress	626
Soybean cyst nematodes	105
Weeds	18
Interactions	93
Total	842

application and use of site-specific pesticide applications or irrigation in (semi) arid areas.

8. Concluding remarks

Precision agriculture has established itself as a series of techniques with the potential to contribute towards the realization of sustainable forms of land management in the future. It is important to realize that there is no such thing as a single tool that will solve all problems. Every problem, varying from low to high-tech or micro- to macro-scales, can require different tools, depending on the problems raised. Researchers should, therefore, integrate their individually developed tools and make them available in a toolbox from which the user of those tools can select. Only through this tool compatibility, problems can be solved optimally. If the right tool is applied for the right problem they can have a relevant contribution to fine-tune operational decision support systems for farmers in future.

Precision agricultural claims, in some cases, to manage fields with resolution of up to 1 m. It can be questioned whether this level of detail is necessary, especially because it will significantly increase the costs of implementing site-specific management whereas management units of, e.g. 0.1 ha may describe the majority of observed variation.

Precision agriculture is certainly not limited to the high-tech approaches as currently being promoted in developed country agriculture. Low-tech, participatory methods also serve very well to apply site- and temporal-specific forms of agriculture. The main challenge lies in the quantification of spatial and temporal variation in crop performance, soil conditions, and pest and disease pressure.

Acknowledgements

Case study I was partly financed by the European Union, DG XII, INCO II. Case study II was partly financed by the European Community project EV5V-CT94-0480 and by the Dutch Board for Remote Sensing (BCRS). The Netherlands Academy of Sciences and Arts funds research of Dr Stoorvogel. The Research Program for Sustainable Agriculture (Guápiles, Costa Rica) is gratefully acknowledged for supporting the research on Case study III. Case study IV is embedded within a research project funded by the Dutch Board for Remote Sensing (BCRS). The Van Bergeijk family is kindly acknowledged for supporting this research on their farm.

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