Spatial soil variability as a guiding principle in nitrogen management

Promotor: Dr. ir. J. Bouma
hoogleraar in de bodeminventarisatie en landevaluatie

Spatial soil variability as a guiding principle in nitrogen management

Jan Verhagen

Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van de Landbouwuniversiteit te Wageningen,
Dr. C. M. Karssen,
in het openbaar te verdedigen
op maandag 15 september 1997
des namiddags te vier uur in de Aula

ISBN 90-5485-737-4

Stellingen

1. Om tot een verantwoorde evaluatie van stikstofbemesting te komen dient ook na de oogst op minerale stikstof bemonsterd te worden.

   Dit proefschrift

   Van der Ploeg, R. R., H. Ringe and G. Machulla. 1995. Late fall site-specific soil nitrate upper Limits for Groundwater protection purposes. J. of Environ. Qual. 24:725 - 733.

2. Het natte winter seisoen in West-europa bepaalt de grenswaarden voor uitspoeling van nitraat.

   Dit proefschrift

3. Het gebruik van afgeleide grenswaarden als "harde getallen" voor milieuwetgeving dient te worden afgeraden omdat deze niet "hard" zijn in ruimte en tijd.

   Dit proefschrift

   Droogers, P. 1997. Quantifying differences in soil structure induced by farm management.

4. Het concept van water-gelimiteerde productie is bruikbaar in de nederlandse akkerbouw bij het bepalen van de benodigde nutrienten input.

   Dit proefschrift

5. Het gebruik van het framework for land evaluation (FAO-1976) is enkel aan te bevelen bij afwezigheid van kwantitatieve bodemkundige informatie.

   FAO. *1976. A framework for land evaluation. Soils Bulletin No. 32, FAO, Rome.*

6. Het algemeen gebruik van marketing termen zoals: produkt, stakeholders en klantgerichtheid dient, om verwarring te voorkomen, gepaard te gaan met specifieke definities.

7. Bodemclassificatie, als communicatie middel naar andere vakgebieden, dient zich te richten op toepassingen van de informatie.

8. Lokatiespecifieke landbouw is landbouw op maat met mate.

9. Agronomisch onderzoek op bedrijfsniveau zal nooit kunnen leiden tot resutaten die direct toepasbaar zijn voor de vele beslissingen die een boer in de praktijk moet nemen.

10. Landbouw is niet schadelijk voor het milieu.

11. Software installaties via een wizard leidden vaak tot een ontgoocheling.

12. Statistiek dient gezien haar wortels bij de staatswetenschappen te worden ingedeeld.

13. Als de wijze waarop men met voedsel omgaat gezien wordt als een maat voor beschaving, scoort de Nederlandse bijzonder slecht.

14. Nadenken kan enkel achteraf.

Stellingen behorend bij het proefschrift " Spatial soil variability as a guiding principle in nitrogen management". J. Verhagen, Wageningen, 15 september 1997.

I thought I saw the fallen blossom
Returning to the tree
But, lo! it was a butterfly.
A Japanese haiku

Aan mijn ouders
Voor Rachma, Anna en Wim

Acknowledgements

The author of this thesis owes a great deal to large number of people. These few lines are dedicated to them. Although all mistakes are mine this work would not have been possible without their support.

First I want to thank my parents for their support over the years.

My promotor Johan Bouma for keeping me on track and for his down to earth advice. Harry Booltink and Hugo Denier van der Gon for the time well spend in room 121 at the department of Soil Science and Geology. Harry Booltink is also acknowledged for his professional input which is reflected in a number of papers on the topic of precision farming. Peter Droogers as a colleague PhD candidate for the discussions on the use of simulation models. Alfred Stein for his advice on (geo)statistical matters.

The students Michiel Sybesma, Peter Verburg, Roel Bout and Chris van Uffelen for their contributions. Chris for his advice on LaTeX matters and for his contribution which resulted in a paper that is included in this thesis.

Piet Peters for his work on the soil physical analyses both in the field and the laboratory. Tom Engelsma for doing the texture analysis in the early stage of the study. Soil chemical analyses were done by Barend van Lagen, Neeltje Nakken, Frans Lettink, Lianne Rou-Haest and Eef Velthorst.

Colleagues Daan Goense and Jaap van Bergeijk from the department of Agricultural Engineering and Physics for the intresting discussions on farming and farm management. Marnik Vanclooster from the Institute for Land and Water Management in Leuven for his support with the WAVE model. Thanks are also expressed to the reader of this thesis.

The staff of the "Prof. van Bemmelenhoeve" and the farm manager Henk Oosterhuis are acknowledged for their cooperation during the three years of field experiments.

Software problems on the UNIX were solved by Kees Bol. The LINUX community is acknowledged for the creation of a near perfect software enviroment for scientists.

I want to thank Theo van der Sluis, who actually read this thesis, for the useful comments on an earlier draft. Ans Verhagen is acknowledged for editing the dutch summary.

Lastly thank you Rachma for your patience and support.

Contents

Chapter 1

Introduction

Environmental pollution associated with intensive agriculture was until rather recently taken for granted and considered unavoidable. This has changed. The condition of our soil and groundwater (a major source for drinking water) has become an important issue in recent years. One of the common pollutants of groundwater is nitrate (NO_3) mainly originating from agricultural practices. Threshold values are defined in national and international laws to reduce emission of pollutants, in order to safeguard the future of the land. Management practices to realise the set thresholds are not well defined nor are the spatial and temporal scales specified at which evaluations have to take place.

The land use potentials of an area are dictated by the soil, the climate and the characteristics of crops (Rabbinge and Van Ittersum, 1995). On farm level spatial variation of soil conditions and (depending on the size of the farm) climate dictate, therefore, the ecological boundaries of the farming system. Farm fields are the management units a farmer has to work with when managing the land (Bouma, 1997a). It therefore seems the correct level to evaluate effects of operational farm management on the environment.

Spatial variability of soil chemical and soil physical properties always occurs within fields (Bouma et al., 1997; Robert et al., 1993, 1995a, 1997). Aggregation to field level without knowing the heterogenity at point level is dangerous. (Rabbinge and Van Ittersum, 1995; De Wit and Van Keulen, 1987). Using field averages for application of fertiliser most likely will result in local under- and over-fertilisation which may lead to suboptimal growing conditions and to leaching of chemicals to the groundwater, respectively. Spatial soil variability is a reality which needs to be addressed in both farm management and in the environmental evaluation of operational farm management practices.

Site specific management aims to address spatially variable conditions. "Fertilise the soil not the field" was already propagated by J. Bouma in 1988 (Van Breemen and Bouma, 1988). Site specific management implies that management practices should vary within fields reacting to local soil and crop conditions. Local optimisation of resources benefits both the farmer in economic terms and the environment in terms of reduction of pollutants. Concepts propagated by site specific farming provide opportunities in low and high tech environments in both large and small scale situations (Bouma et al., 1995; De Steenhuijsen Piters, 1995).

De Wit (1992) pointed out that the optimum law of Liebscher[1] has a general validity because agriculture requires the management of growth and production processes in a partly controlled environment. De Wit concludes that most production resources are used more efficiently with increased yield level due to optimisation of growing conditions. When fine-tuning the application of agrochemicals to the plant the efficient use of these compounds is improved. Fine-tuning of farm management measures, in terms of time and space, is therefore the core activity of precision agriculture (Bouma, 1997a). Strategic research that is to serve both agriculture and its environment should be directed mainly towards the search for the minimum of each production resource that is needed to allow maximum utilisation of all other resources.

This thesis focuses on the optimisation of N fertiliser application, taking into account spatially variable soil conditions, taking the position that prevention of groundwater pollution is favoured above purification of polluted groundwater. Pollution prevention is best served by efficient use of N fertiliser. The study area is a field on the experimental farm "De Van Bemmelenhoeve" in the north western part of the Netherlands. The work presented in this thesis continues the work done by P. A. Finke on spatial variability of soil structure which was carried out on the same farm, but on a different field (Finke, 1992).

Simulation modelling plays a central role throughout this thesis. This is new in site specific management where emphasis appears to be on technology while agro-ecology receives relatively little attention (Robert et al., 1993, 1995a, 1997). Amongst others, Addiscott (1993), Hoosbeek and Bryant (1992) and Bouma and Hoosbeek (1996) present classification systems for simulation models. All these systems make the distinction between deterministic and stochastic models. Deterministic models ignore uncertainty in the simulation outcome whereas stochastic models accommodate this uncertainty. A second distinction is made between mechanistic and functional or empirical models. A mechanistic model is aimed at describing the mechanisms of the processes, while a functional models aims to give a good general description of the effects of the process without clarifying the process itself. In this study the model WAVE (Vanclooster et al., 1994) is used. The model was developed in the context of an EU funded project by researchers

[1]Liebscher's law is know as the law of the optimum and states that a production factor that is in minimum supply contributes more to production the closer other production factors are to their optimum.

in Leuven University. WAVE is a combination of four existing models of different origin. The water and solute transport models represent the core of WAVE. Both are classified as deterministic and mechanistic. The nitrogen and crop growth models can best be described as deterministic and functional models. The model is generally classified as a deterministic/mechanistic simulation model.

Models need input of information. In WAVE the soil physical characteristics are key parameters. These parameters determine the movement of water and solutes which governs the availability of water and nutrients to the crop. Wösten et al. (1986) developed a method to identify soil layers that have different hydrological properties. This approach was used by Finke and Bosma (1993) and later by Verhagen et al. (1995b) to identify so called functional layers for the study area. Each individual soil profile is described as a sequence of functional layers of varying thicknesses. The physical information for each soil profile is regarded to be static in both space and time[2] and serves as the first layer of information for scenario analysis. By using simulation models we have the opportunity to explore the dynamic behaviour of the soil under various boundary conditions., which may represent future conditions. Careful calibration and validation by field data has contributed towards reliability of results obtained.

When searching for optimal N fertilisation levels combining low leaching quantities with high production levels, simulation models are powerful tools. Simulation models for point data in combination with geostatistics are used to address soil quality issues at field level. We always have to look simultaneously at quantity and quality of agricultural production and to environmental quality, as well, as they are important elements of sustainable agricultural production systems (Bouma, 1997a). In this thesis both items are addressed in quantitative terms, separating conditions in the growing season from those in the wet winter season when most leaching occurs. Finally, the issue is addressed as to how threshold-values for N contents at the end of the growing season, as defined by winter leaching, influences management during the growing season.

In summary the objectives of this study were:

1. To measure spatial and temporal variability of soil physical properties, yield and N for a farm field.

2. To quantify spatial and temporal variability, using simulation modelling and geostatistics, of:

   (a) crop production and nitrate leaching.

   (b) effects of N fertiliser management on production and leaching.

[2]Not a geological time frame but time frame related to a more human scale i.e. decades.

3. To identify areas in the field with comparable behaviour with respect to production and leaching, considering the effects of multi-year weather variation in both the growing season and the season with precipitation surplus.

4. To define representative profiles for the identified map units using two land quality indicators: nitrate leaching and crop production.

The outline of the thesis is as follows:

i. The first part introduces the reader to the study area and describes the tools used to quantify spatial and temporal variation to the experimental field. Objectives: 1, 2

ii. The second part deals with the implications of spatially variable soil conditions on farm management. Both production and leaching are discussed. Objectives: 2, 3

iii. In the final part the combination of production and leaching is discussed for the experimental field. By using the representative profile concept a proposal is made for the next step: from field level to farm level. Objectives: 3, 4

The individual sections have also been submitted and approved as scientific publications covering research on site specific farming at the "Van Bemmelenhoeve" over the last four years. Some aspects are, therefore, repeated among the various sections and units may vary in the different sections as different journals have different criteria. The bibliography, however, is compiled and presented at the end of the thesis.

The work done was part of a project funded by the European Union under the EU–AIR project 94 – 1204 (IN–SPACE): "Reduced fertiliser input by an integrated location specific monitoring and application system.", coordinated by Dr. D. Goense, Wageningen, the Netherlands. The datasets used in this study were used in the Summerschool on precision agriculture (1995) coordinated by Dr. H. W. G. Booltink at the department of Soil Science and Geology. Currently the datasets are being implemented in the course "Quantitative analysis of (agro–eco)systems at higher intergration levels *Landevaluation and variability for explorative land use studies* (QUASI). The data sets used are available from the department of Soil Science and Geology, Wageningen Agricultural University.

Chapter 2

Mapping in space and time by interpolation of simulated point data

2.1 Characterisation of spatial variability of yield and leaching for the experimental field[1]

Abstract

Spatial variability of soil conditions and potato growth were studied in a 6 ha farmers field in a Dutch polder. Potato yields, measured in 65 small plots varied between 30 and 45 tons ha^{-1}, while yields of commercially attractive large potatoes varied between 3 and 15 tons ha^{-1}. Such differences are economically significant for a farmer. A system for site-specific management is discussed including site specific sampling for soil fertility and use of dynamic simulation modelling to characterize soil water regimes and nutrient fluxes, e.g. of nitrate. Total N in the early part of the growing season varied between 21 and 53 kg ha^{-1}. Site specific fertilization rates can be based on such values. When compared with recommended rates obtained from one mixed sample for the entire field, local over- and underfertilization can be demonstrated. These are bound to lead to groundwater pollution and inefficient production. Modelling can be used to balance production and environmental aspects in a quantitative manner, as is demonstrated. Data needs of the WAVE model, used for simulation of yields and nitrate fluxes, are discussed including distinction of only four "functional layers" for the 6 ha field, which define all variability in basic hydraulic characteristics. Technical developments in site specific technology are briefly reviewed. Fine-tuning of management practices, including fertilization, appears to be an attractive and practical procedure to use natural resources more efficiently.

---

[1]*based on:* Verhagen, A, Booltink, H. W. G. and Bouma, J. 1995. Site-specific management: balancing production and environmental requirements at farm level. Agricultural Systems 49:369 – 384.

Introduction

Sometimes a technological breakthrough has unexpected side-effects. The development of global positioning systems (GPS), initially in secret for the military but later openly aimed at a large group of prospective buyers, has by now resulted in the availability of relatively cheap gadgets allowing accurate determinations of locations at the earth surface at any time. When applied on harvesters which are also equipped with sensors for continuous yield monitoring ("yield monitoring on-the-go"), some interesting results are being obtained (e.g. Rawlins et al., 1995). Differences in crop production within agricultural fields, which are the management units for a farmer, turned out to be much higher than anticipated, often ranging from a factor two to four. These results are new. Farmers would know, of course, that differences occur but such impressions were always hard to quantify because documentation by making a series of small harvests within a field, was obviously not feasible from a management point of view. Yields are therefore always expressed in terms of e.g. tons ha^{-1}, by dividing total yields by the total area of the farm being covered by a particular crop, ignoring local differences. Application of GPS and yield-sensing equipment does, however, allow expression of such differences.

What are the implications of knowing yield differences within fields? The first challenge is to find the reasons why these differences occur and the second challenge is to then develop management procedures which can reduce these differences. The overall expectation would be that reducing differences would be economically attractive for the farmer and ecologically attractive for the farmer and for society at large. Even though such expectations would appear not to be unreasonable, specific research is clearly needed to prove the point.

Yield differences within fields can be due to many reasons, such as: differences in actual soil fertility or to unequal application rates of fertilizers or biocides; occurrence of compacted layers; low and wet spots or high and dry spots; local occurrence of pests and diseases and many other reasons. Once reasons have been established, site-specific management procedures have to be devised which allow local rectification of differences. This requires development of new technology, where, again, GPS plays a central role.

Research, as discussed here, has been in progress in several countries with a clear focus on soil fertility. The traditional manner to collect soil fertility samples is to obtain a mixed sample from a field and to derive a one corresponding fertilizer recommendation by using standard tables relating fertilization rate to yield. Obviously, this procedure will underestimate rates for some areas and overestimate them for others. This implies local overfertilization, leading to leaching below the rootzone and possible groundwater pollution, and local underfertilization implying inefficient use and suboptimal production conditions. Several studies

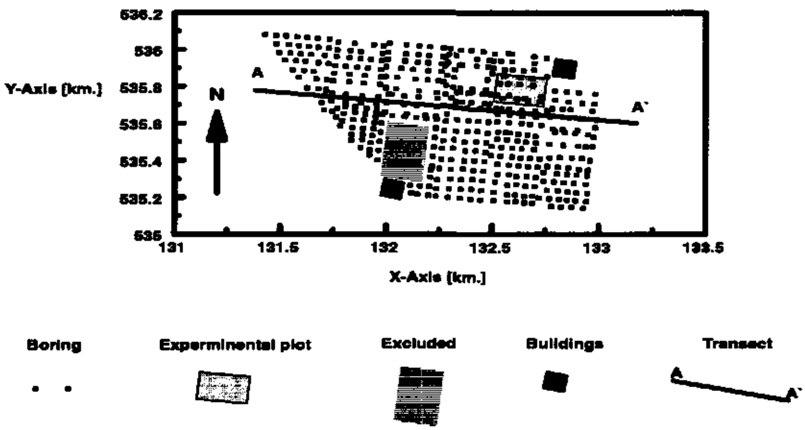

Figure 2.1: *Layout of the experimental farm "Prof. van Bemmelenhoeve", Wieringermeer, the Netherlands.*

have been reported where many separate samples were taken and where fertilization rates were determined for each point (Franzen and Peck, 1995). Information technology, such as Geographic Information Systems, and computer-guided application devices were used to achieve what has been called: "soil or site specific management". Varying the applied amount of fertilizer within a field based on site-specific fertility analysis, has saved money (from \$10 – \$80 per acre on average) and has reduced leaching of excess fertilizer beyond the rootzone.

As discussed above, other factors than soil fertility could well be the cause of yield differences within fields. Recently, therefore, the term: "precision agriculture" has been coined to cover all factors of location-specific management, including technologies and software.

This paper will address the question which soil related research is necessary to allow execution of precision agriculture, and how research should proceed. Some first results of an exploratory, ongoing study will be presented, which is being made in the Netherlands.

Soil research for precision agriculture

The following elements may be distinguished when defining soil research for precision agriculture to be focused on specific fields of a given farm.

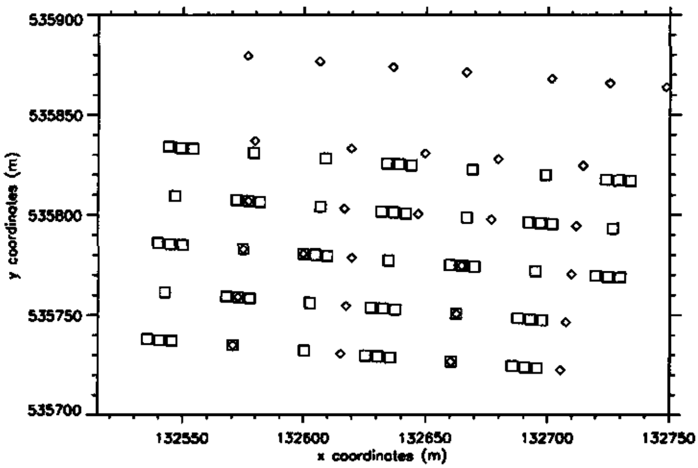

Figure 2.2: *Layout of the experimental plot with harvesting and monitoring pits.*

1. Establish a soil database, which contains relevant soil characteristics.

2. Monitor crop growth and physical and chemical conditions during one or more growing seasons. Use data in expert systems and for calibration and validation of simulation models for crop growth and solute fluxes.

3. Define threshold values for yields and chemical fluxes from an economic and environmental point of view and determine when they are exceeded under different well defined forms of management and variable weather conditions.

4. Use modelling techniques to define management schemes that avoid exceedance of threshold values while maintaining yields at economical levels.

5. Implement the schemes by developing and using site-specific technology.

6. Develop operational decision support systems to be used in practice.

The above elements will now be discussed in more detail, providing examples from literature and from an ongoing case study in the Netherlands for an experimental plot at the experimental farm: the Van Bemmelenhoeve, in Wieringermeer, the Netherlands.(Figure 2.1).

Soil database

The Farm Van Bemmelenhoeve in the Wieringermeer, the Netherlands (Figure 2.1) was studied. Particular attention was paid to a field, shown in Figure 2.2, with dimensions of 300 m by 200 m. An exploratory soil survey was made and soils were classified as Typic Udifluvent (Soil Survey Staff, 1975). Each observation was geo-referenced. In contrast to a traditional soil survey, attention was focused here on "functional" soil horizons and not on the traditional genetic horizons. Functional horizons consist of combinations of genetic horizons with identical behaviour. Here, physical properties are used to distinguish functional horizons.(e.g. Finke, 1993). In this field, soils were strongly layered and distinction of functional layers was based on descriptions of soil texture, as observed during augering, and a preliminary classification that was finalized after measurement of hydraulic conductivity and moisture retention data, using modern techniques (e.g. Finke, 1993). Four functional horizons were distinguished, as summarized in Table 2.1, which also lists the van Genuchten coefficients for the measured hydraulic characteristics. Average measured Hydraulic conductivity and moisture retention data of each of the four layers are shown in Figure 2.3.

Use of functional horizons is attractive because the vertical sequence of layers at each point observation can be represented by only a few, and sometimes only one, functional horizon, rather than a relatively high number of pedological horizons. A representative cross section through the field of study, in which each depth is characterized by a functional layer is shown in Figure 2.4. Basic hydraulic soil data can be used for simulation modelling for each point, as will be discussed later.

Geo-referenced soil data, as collected here, are quite different from data derived from conventional soil maps, even highly detailed ones. Soil maps define mapping units in which a particular soil type is assumed to occur, while attention in this study is on defining point data in terms of characteristics which are relevant

Table 2.1: *Description of the functional layers and corresponding van Genuchten parameters for the hydraulic functions. Standard deviation between brackets.*

Layer	ρ [kg dm^{-3}]	*Org. matter* %	*Clay* %	K_{sat} [cm day^{-1}]	θ_{sat}	θ_{res}	α	n	l
F1	*1.48* (0.039)	*0-2*	*0-4*	*183*	*0.40* (0.02)	*0.02*	*0.03096*	*2*	*2.2842*
F2	*1.21* (0.079)	*0-2*	*4-11*	*128*	*0.48* (0.04)	*0.03*	*0.01949*	*1.32633*	*4.46260*
F3	*1.08* (0.231)	*0-2*	*11-23*	*36*	*0.59* (0.06)	*0.01*	*0.02824*	*1.17160*	*7.40090*
F4	*1.30* (0.045)	*0-3*	*4-23*	*265*	*0.44* (0.08)	*0.00*	*0.05524*	*1.13394*	*10.25272*

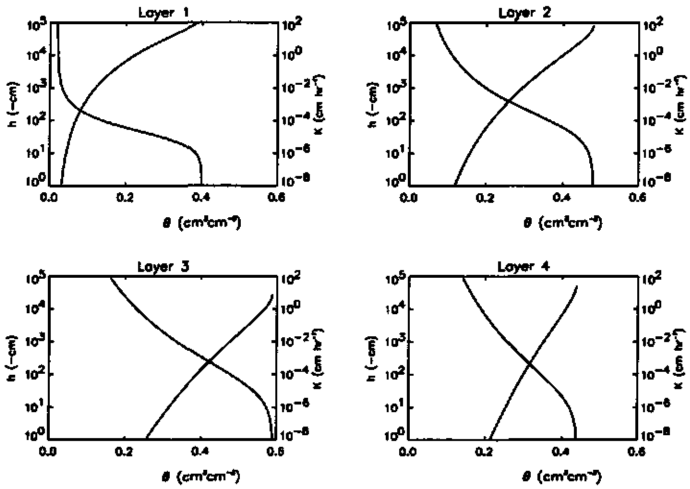

Figure 2.3: *Average moisture retention and hydraulic conductivity data for the four functional layers. Averages are based on five replicate measurements.*

for modelling. Expressions for areas of land are obtained by interpolation of point data (e.g. Finke, 1993).

Crop growth and soil conditions: expert systems and models

Advisory schemes for soil fertilization have been used quite successfully for more than 60 years. They relate actual soil fertility to fertilization rate and expected yield and are based on field experimental data. Of course, such relations are complex and depend on many factors, which are not expressed in the schemes. For instance, effects of different weather conditions in different years and soil hydrology as well as effects of different soil types. In general, the advisory schemes take into account soil differences but only in broad terms, such as clay soils versus sand soils. As coarse as the schemes may be, they proved to be sufficiently reliable to allow estimates between actual soil fertility, fertilization rates and expected yields, although the latter are often not specified. Of course, the schemes are exclusively focused on crop production. No attention is paid to possibly adverse environmental side effects such as soil and water pollution.

Advisory schemes are suitable to explore expected effects of site specific management. In the field being investigated, 30 soil fertility samples were taken. Also a composite sample was made. Each sample was interpreted in terms of fertilization rate and expected yield. Results are summarized in Figure 2.5, which shows total N as measured on June 8. The map was obtained by interpolation, using

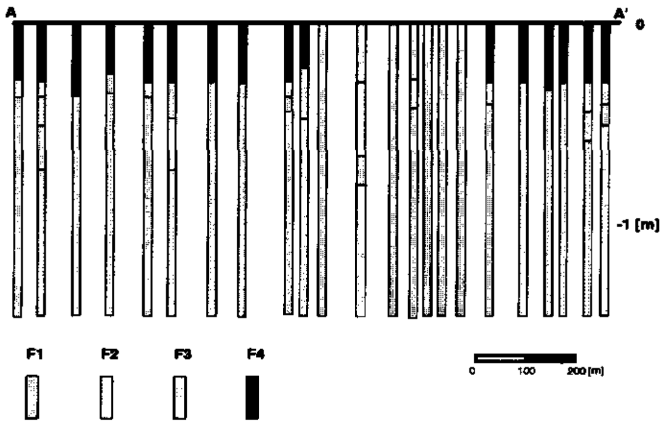

Figure 2.4: *Cross section of soil profiles along the line A-A' in figure 2.1. Each profile is composed of a number of functional layers.*

the kriging technique, of 30 point data. Using computer simulation models for crop growth and solute fluxes represents a modern and more detailed method to express relations between crop growth and soil conditions (Teng and Penning de Vries, 1992). Models can be used to express both crop growth and environmental effects.

Different types of models can be distinguished. In our work, use is made of the WAVE model for simulating water movement, nitrogen transformations and crop growth. This model was developed in the context of an international program financed by the European Union. In this study potato yields were measured by harvesting 65 small plots. These values were interpolated and results are shown in Figure 2.6.

Yields vary between 30 and 45 ton ha^{-1}, which represents a significant range. More important than total yield is the yield of potatoes with a diameter of more than 50 mm. (Figure 2.7). These potatoes are well marketable for chips. Differences are pronounced, and range from 3 to 15 tons ha^{-1}. The smallest values are obtained in areas with the lowest yields. For example, total yields of 30 tons ha^{-1} correspond with a yield of large potatoes of 3 tons ha^{-1} (10 %), while total yields of 45 tons ha^{-1} correspond with yields of large potatoes of 12 – 15 tons ha^{-1} (30 %). Here, yields were measured. They can also be simulated. However, measurements are always to be preferred, if feasible, in view of uncertainties associated

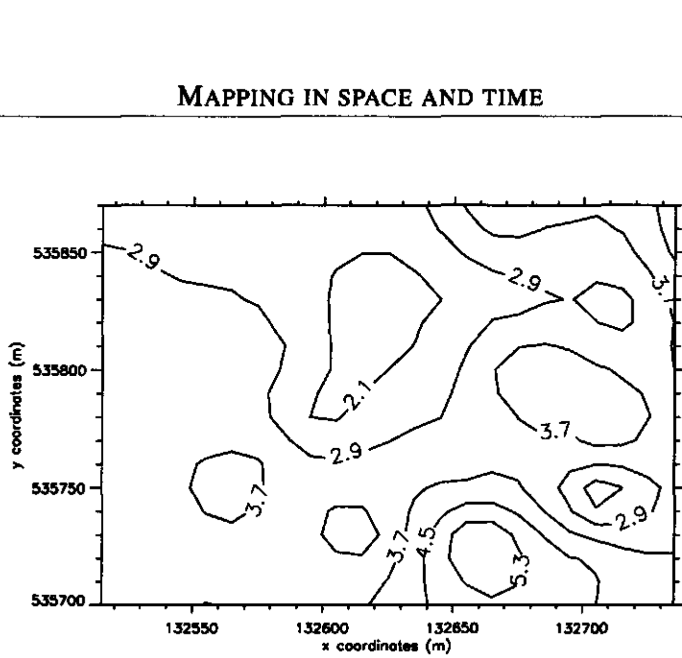

Figure 2.5: *Total N (ton ha^{-1}) at June 8, for a depth of 0-60 cm. below surface.*

with modelling. In this context we also show Figure 2.8 containing measured leaf area indexes, obtained with a hand-held crop scan apparatus. In general terms, patterns of leaf area indexes measured on August 3 correspond reasonably well with the yield patterns measured in September. In all these examples, point data were interpolated to areas of land by using geostatistical techniques (Finke, 1993). The WAVE model was used to calculate water and nitrate fluxes for the growing season of 1994. The penetration of nitrates proceeds quicker and to a relatively greater depth in the more sandy soil. The model was used here for real time conditions. Of course, use of simulation models is particularly attractive when making runs for weather and soil conditions in different years.

Exceedance of threshold values of selected indicators

The overall objective of: "precision agriculture" is to manipulate nutrient (and biocide) fluxes in such a way that conditions for crop growth and development are maximized while unfavorable environmental side effects are minimized.

To judge both the level of crop growth and environmental side effects we need indicators and their threshold values as a reference. Indicators are defined as environmental statistics that measure or reflect environmental status or change in condition, while threshold values represent levels of environmental indicators beyond which a system undergoes significant change: points at which stimuli provoke significant response (FAO, 1993). For our case study, soil water content and

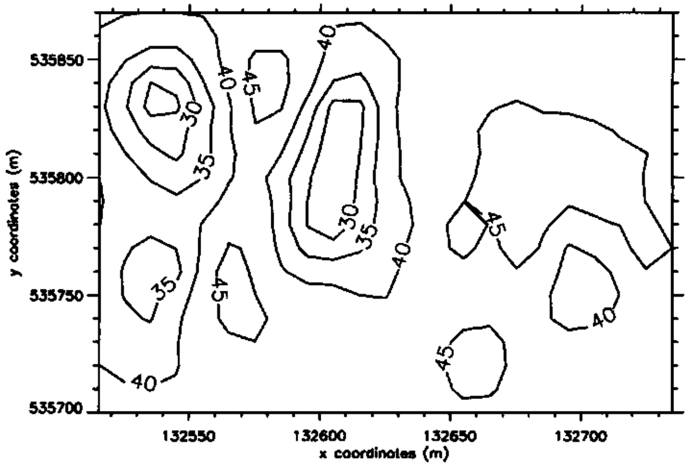

Figure 2.6: *Total potato yield (ton ha^{-1}) in 1994.*

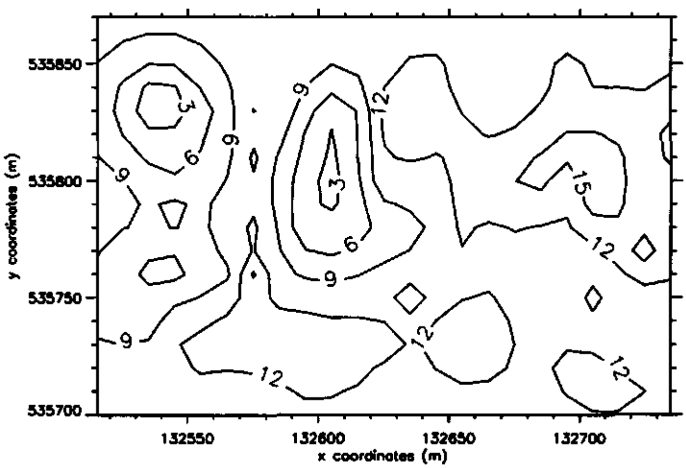

Figure 2.7: *Yield (ton ha^{-1}) for tubers with diameter larger than 50 mm.*

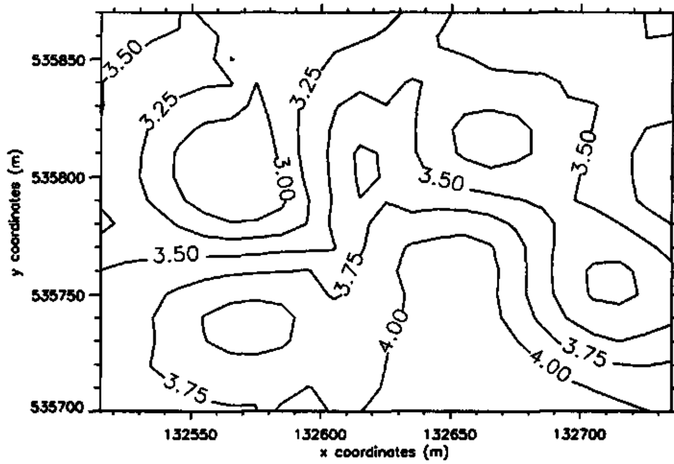

Figure 2.8: *Leaf area indexes (LAI) measured on August 3 1994. Patterns were obtained by interpolating 80 point measurements.*

nitrate fluxes in the soil are two obvious indicator values. Without the models, there simply would not be enough time nor funding to generate the large number of data needed to test and implement the concept. Implementation gives rise to a number of questions:

(i) which indicators relate to crop production and which to environmental aspects.

(ii) what are the threshold values for these indicators.

(iii) how feasible is it to have not only common indicators but common threshold values as well for the soil functions being considered.

For our example, we may consider soil water content and nitrogen content as indicators. Both are important for crop growth and environmental conditions. First, then, the water content of the soil. The dry months of July and August have reduced crop growth considerably. The model calculates potential versus actual transpiration. Simulation models can also be used to show how much water should have been applied at what time to allow potential transpiration to occur. The nitrogen content is more difficult to characterize. Crop demand is a function of the growth stage; downward fluxes of nitrate are a function of the amount of N in the rootzone and the water content, which is directly associated with the flux. Simulated downward nitrate fluxes can be interpreted directly in terms of exceedance of a critical threshold value for leaching by drawing a horizontal line at the threshold level and by counting the number of days that the concentration of nitrate in the percolating soil water was higher than a selected critical threshold of, say, 50 mg liter^{-1}. At the same time, N needs of the crop can be determined for any period in the growing season when aiming for nutrient unlimited yield. This determination represents a more sophisticated approach to the problem of determining relations between nutrient status, fertilization and yield as discussed earlier. Clearly, in defining an optimal system, requirements defined for production have to be balanced against requirements for environmental quality.

Balancing yields and solute fluxes

The example discussed in the previous section demonstrates the need to balance requirements for production on the one hand and for environmental conditions, on the other. The analysis for the indicator: "water content" resulted in a definition of periods during which water could be applied to achieve potential production. However, this could result in unacceptably high downward flows of water and nitrates, considering accepted threshold values. So before a recommendation about irrigation can be made, the model should be used to check whether such fluxes would indeed be probable. If so, it may not be possible to add all the water that would be needed to achieve maximum production from a hydrological point of view. Consideration of the other indicator: "nitrogen content" leads to a similar analysis. Adding more nitrogen at particular times during the growing season on the basis of crop requirements, may lead to unacceptable nitrate losses, certainly when additional water would be applied to combat drought stress.

When analysing this balance between yield and solute fluxes, the scenario approach can be used in which a series of variants are run by the model. One can be chosen as being the best compromise.

So far, only real weather conditions in the growing season of 1994 were considered. Conditions are different in different years and models can, again, be used to characterize such conditions. This will be done as the study is continued.

Implementation by site specific technology

Once point data are obtained with procedures described in the previous section, we have to consider spatial differences. As stated above, these can be derived from point data by interpolation techniques (see Figures 2.6, 2.7 and 2.8). Next, technical means have to be defined to use those differences with the purpose to obtain a better production system from a balanced ecological point of view. No new original research results will be presented here, but work elsewhere will be briefly reviewed. Interesting developments occur in the USA, UK and Germany in terms of development of site specific technology, including GPS guided fertilization machinery (Robert et al., 1995b; Murphy et al., 1994a). Machines need to be fed with proper spatial data and this still presents a major challenge to research.

Operational decision support systems

So far, precision agriculture appears to be mainly focusing on defining site specific fertilization. Modern machinery has been developed to allow spatial differentiation of fertilization. To define site-specific rates, most often classical assessment schemes are used which are based on field experiments and which relate actual nutrient status to advised fertilization rate and expected yield. Clearly, simulation modelling can help to fine tune such rather crude prediction systems. Still, models need to be validated and have high data demands which can not always be satisfied. The questions needs to be raised how models can play a role within operational decision support systems, which need to be pro-active rather than reactive. A farmer is primarily interested to know what he should do for the coming weeks and months, not in what happened last year. At this time, it is unclear which type of data are needed in an operational decision support system. Likely, the accuracy of medium -term weather predictions could be a deciding factor in determining the degree of detail of other agronomic and soil data needed in the DSS.

Conclusions

1. Experimental field work in a marine clayey soil in the Netherlands has demonstrated occurrence of significant differences in potato yields within a farmer's field of 6 ha. Total yields varied between 30 and 45 tons ha^{-1}, while yields of commercially attractive large potatoes varied between 3 and 15 tons ha^{-1}. Such differences are not unusual and are quite significant from an economic point of view.

2. Differences in yield can be due to many factors that were explored in this study. Computer simulation techniques can be used to calculate water and nitrate fluxes which govern both production and environmental side effects of the production system. Simulation techniques are important as exploratory tools in finding an acceptable balance between production and environmental pollution. ICASA software is well applicable in this context.

3. A new type of soil survey was discussed which allows distinction of so called functional layers, to be characterized in terms of field properties such

as texture, with typical hydraulic characteristics. The highly complex stratified marine soils of this study could be represented successfully by only four functional horizons.

4. Fertility samples, taken within the 6 ha field, showed a large variation. Recommended fertilization rates, based on point data differed significantly from those based on one mixed sample for the entire field. The latter procedure resulted in local over- and under fertilization.

Acknowledgements

The work reported is part of a project funded by the European Union under the AIR3 programme (Project 94_1204). The authors wish to acknowledge the assistance of the staff of the Research Station for arable farming and field production of vegetables (PAGV) experimental farm the "Prof. Dr. J.M van Bemmelenhoeve".

2.2 Use of a simulation model to characterise soil related spatial variability [2]

Abstract

In this paper spatial and temporal soil variability are characterized using simulation modeling and geostatistics. To facilitate modeling use is made of the functional layer concept. Functional grouping was based on soil physical criteria. Modeling is crucial to characterize spatial and temporal variability because field measurements can never cover the range of conditions that are relevant to questions dealing with agricultural production and environmental quality. The use of process based models which allow linkage to farm management is advocated. The model WAVE allows simulations of both crop production and nitrate leaching.

Variability in potato production was successfully simulated for 1994. Simulations took in account yield reduction resulting from water and nitrogen stress. Fertiliser scenarios are simulated for 1994 and effects on production and leaching of nitrate are discussed. Using historic climatic data the model is used to explore the behaviour of the field over space and time. Stable patterns, in space and time, are used to derive a prototype pattern for site–specific management.

Expanding existing soil databases with simulation results is posed as an atractive option to incorporate the dynamic behaviour of soil series thus defining a specific "window of opportunity" for each soil series.

[2] *published as:* Verhagen, J. and Bouma, J. 1997. Modelling soil variability. In: Pierce, F. J. and E. J. Sadler (editors). The state of site specific management for agriculture. ASA Misc. Publ., ASA, CSSA and SSSA, Madison, WI. pages: 55 – 67.

Introduction.

When dealing with site-specific management (SSM) soil variability is a key element. Variability is dealt with in terms of space and time, both for point observations and characterizations for areas of land more particularly, fields. The simplest way to obtain such characterizations is to make direct observations or measurements of variability for a period of time. Measurements focus on elements of importance for site specific management, such as crop growth and soil water and soil nutrient contents during the year. New attractive techniques are now available to make such observations and measurements. In situ sensors are available for water (TDR) and, still experimental, for nitrate. Remote sensing techniques applied from satellites, airplanes, or handheld equipment provide continuous indicators for crop growth and crop health. However, these techniques are costly and complicated and it is hard to see how site-specific management could be based exclusively on these techniques, if only because future developments of soil conditions can never be taken into account when only actual conditions are characterized. A farmer wants to base his management also on expected future conditions, which are largely determined by the weather. However, the rapid introduction of Global Positioning Systems (GPS) and on-the-go yield monitoring sensors (Murphy et al., 1994b) presents a wealth of data on crop yields for each growing season, which, in time, may present characteristic patterns that may serve very well as a basis for SSM. Still, SSM ideally should consider the entire crop-soil system, including fluxes of solute. These, of course, will not be provided by on-the-go yield monitoring.

An attractive alternative to measurement of crop growth and solute fluxes is therefore dynamic simulation modeling to predict crop growth and nutrient fluxes. Model runs can be based not only on actual but also on historic weather data. Historic data can be used to make predictions for future conditions using statistical techniques. Of course, results of simulation runs should always be validated with real data, obtained by measurements as mentioned above, for a limited period of time, e.g. a few growing seasons.

Of particular interest, when discussing site-specific management, are predictions of soil behavior in different areas of a field.

Different types of models.

A lucid discussion of models and their data needs has been presented by Addiscott (1993). A model is a simplified representation of reality. A distinction can first be made between deterministic and stochastic models. A deterministic model presumes that a certain set of events leads to a uniquely definable outcome, while a stochastic model presupposes the outcome to be uncertain and is structured to accommodate this uncertainty. A second distinction is between mechanistic and functional models. Mechanistic models seek to describe the fundamental mechanisms of the process, while a functional model aims to give a good general description of the process without going into details. A third practical distinction between models is that of purpose. Some models are used in research while others are used as management tools. When dealing with SSM, we have used deterministic and mechanistic models, as tools to assist in management decisions (LEACHN: Finke 1993; WAVE: Vanclooster et al. 1994). Emphasis on recognizable processes that can be associated with management practices requires a deterministic approach. The question as to whether a mechanistic or functional model is needed is more difficult to answer, because mechanistic models need more data. Still, our desired emphasis on processes and their quantification clearly requires a mechanistic approach, rather than the "black-box" approach of functional models. The question as to whether enough data are available to allow use of mechanistic models is a crucial one. Increasing data demands for modeling can, however, partly be met by developing continuous- and class-pedotransfer functions, which relate available soil data to parameters needed for modeling (e.g. Bouma and Van Lanen, 1987; Bouma, 1989)

SSM applications add one specific aspect to model considerations, which is the forward- and backward looking approach. Weather data drive models for plant growth and solute fluxes. When modeling with historic data, we can reproduce conditions as they occurred in the past. However, SSM requires predictions for the (near) future on which management decisions are to be based. Perhaps weather forecasts for, say, two-week periods can be fed into a mechanistic model, which then predicts crop growth and solute fluxes. If results are likely to be unsatisfactory, field management can be adjusted and the model can again be used to predict the possible effects of different alternative land-use scenarios. This may, however, be too farfetched and using historic data for a wide variety of years may be more realistic. As an actual year progresses, weather data can be taken from the historic database that corresponds more or less with the actual progression of weather patterns during the year. There are indeed certain consistent trends to be recognized, corresponding with "wet", "dry" and "early", "late" years. Calculated crop yields and water and solute contents for each of such "historic" years can then be taken from the database and be used as predictors for conditions in the actual year being considered. Descriptive terminology, as indicated, facilitates communication with farmers.

Soil variability: pedological and functional

To model variability requires first a proper definition of variability. Variability of what? Soil parameters vary, but variation may not be significant in a functional sense. For instance, variations in soil texture may not result in significant differences among the corresponding hydraulic characteristics. Sometimes pedologically identical soils behave differently, sometimes different soils behave the same. Management practices can have a major effect on soil properties in a given soil series (e.g. Bouma, 1989). Introduction of "functional" soil horizons, which are a combination of different pedological horizons with identical behaviour, is an attractive procedure as it simplifies modeling by requiring fewer input data. Wösten et al. (1985) considered the hydraulic behaviour of soil horizons and could reduce data demand by a factor three. However, soils have different functions and different soil horizons may act identically for a given function but act differently for another function. For instance, Breeuwsma et al. (1986) showed that the function of adsorbing phosphates led to a different grouping of horizons, as compared with a grouping based on hydraulic characteristics. The major point to be made here is the need to express variability in terms of functional and not pedological differences (e.g. Wilding et al., 1994; Wagenet et al., 1994). As SSM focuses on water and solute fluxes, functional groupings of pedological horizons should be on the basis of hydraulic and soil chemical characteristics.

From variability in point data to field variability

A key element in SSM is patterns in fields, as they relate to yield differences, occurrences of pests, diseases, etc. Soil science, and particularly soil survey, has had a long history of providing patterns as they are shown on soil maps. The basis for these patterns are pedological differences as expressed by the legend of the map, which is based on criteria from soil classification. As stated above, we are not really interested in pedological differences but, rather, in functional differences within fields which are relevant for SSM. So rather than use patterns of existing soil maps, we prefer to model for point data and use interpolation techniques to extend results to areas of land. (e.g. Finke, 1993). Thus the variability within mapping units of the soil map, present within a field, is also expressed. The question as to how many point observations should be made within a given field is a crucial one. Geostatistical techniques, which define variation between point observations as a function of distances between points, allow a quantitative assessment of the optimal number of point observations. (e.g. Stein et al., 1988). Thus, the number of observations is determined by the variability of the area to be characterized rather than by the scale of the map to be made, which was often the criterion in earlier times. Many geostatistical techniques are available (e.g. Burrough, 1993) but disjunctive kriging and indicator kriging have been used with particular success because they allow expression of spatial patterns in terms of probabilities of exceedance. So rather than present results of interpolations in terms of fixed classes of values, we can present results in terms of the probability that a given

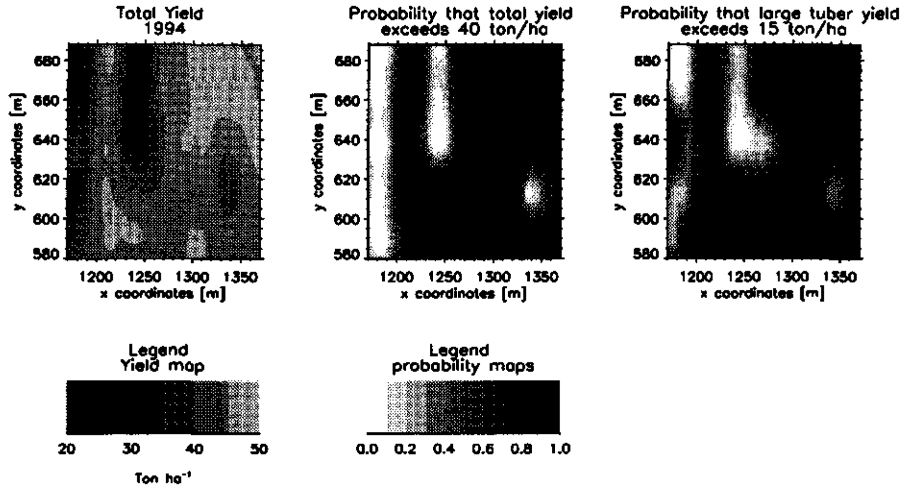

Figure 2.9: *Example of probability maps created with indicator kriging. Interpolated maps are based on measured data. Ordinary kriging was used to create the first map which shows the spatial pattern of total yield for the 1994 growing season. The adjacent two maps are created using indicator kriging.*

value is exceeded. An example is shown in Figure 2.9 , which presents three maps. The first map shows the actual yield map. Next the probability that a certain production level is exceeded for the 1994 growing season is presented. The third map presents the probability that the large tuber yield (>50 mm) exceeds 15 ton ha^{-1}. When running a model for a given point observation, realistic results are obtained when the accuracy of results obtained is expressed. This implies that rather than running only average values for, e.g., the hydraulic conductivity and moisture retention, also the variability in these values should be expressed. Techniques, such as the Monte Carlo techniques, are available to express the accuracy of data obtained as a function of the variability and reliability of input data. Examples are provided by Booltink (1994) and Bouma et al. (1996).

The above discussion dealt with running a model for one growing season. However, variability in time over a period of different growing seasons is very important for SSM, because weather conditions in any given year determine the most appropriate SSM procedure. Simulation modeling is a particularly attractive way to make multi-year runs for production and associated solute fluxes. The next question concerns the comparison of different interpolated maps. Visual comparisons are a logical start but more quantitative approaches are needed to allow transferability of results obtained. Following the approach by Davis (1986) Van Uffelen et al. (1997) developed a new procedure to compare different maps, as

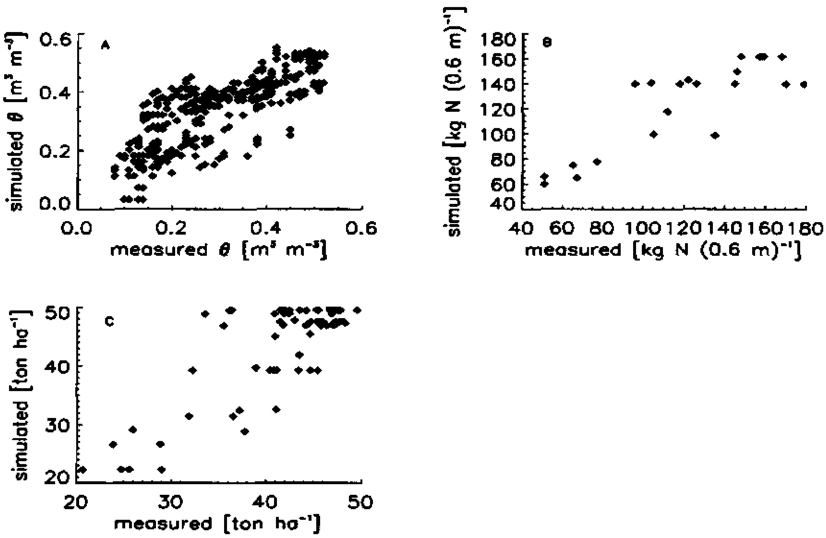

Figure 2.10: *Validation of the model. (A) watercontent (R^2 0.65), (B) mineral nitrogen [0-60 cm] (R^2 0.58) and (C) End Yield (R^2 0.65)*

will be discussed in the next section.

Modeling variability: a case study

The above discussion will be illustrated with a Dutch case study in a field of an experimental farm in the Wieringermeer polder. A detailed account cannot be presented here because of space limitations. Reference will be made to other publications where results are presented in more detail, while emphasis here is on using modeling in the context of SSM, with its implications, problems and opportunities. (Bouma et al., 1995, 1996; Verhagen et al., 1995a).

The field being used occurs in young, stratified marine sediments with varying textures at relatively short distances. In devising a research scheme with modeling of variability as a central theme, the following steps were taken:

1. A soil survey on farm field was done on a regular grid including short distance observations.

2. Hydraulic conductivity and moisture retention data were measured in different soil layers that were distinguished on the basis of textural differences.

Systematic testing of differences resulted in the distinction of four, significantly different functional horizons that were used in the following simulations.

3. Soil water contents at several depths and yields of potatoes and wheat were measured during two growing seasons: potatoes in the first year by harvesting 65 small plots, wheat with a GPS-monitored combine with automatic yield registration equipment. Remote sensing images were obtained to characterize conditions of the crop.

4. Simulation runs were made with the WAVE model for real-time conditions in 1994 allowing calibration and validation of the model (Figure 2.10). Runs were made for point data.The validated model was used to calculate yields and solute fluxes for seven fertilizer scenarios for 1994.

5. Yield patterns were calculated using ordinary kriging. Nitrate leaching risk patterns were made using indicator kriging, allowing spatial evaluation of the fertilizer scenarios on both yield and leaching of nitrate (Figure 2.11).

6. The validated model was used to calculate water-limited potato yields for seven years with different weather conditions (Figure 2.12). Water-limited yield was chosen because it is an indicator of management-independent (for non-irrigated crops) production levels. The generated yield patterns were compared and a general pattern was derived, to be used for future site-specific management (Figure 2.13).

In Figure 2.11, the spatial patterns of yield and nitrate leaching risk for three fertilizer scenarios are shown. The nitrate leaching patterns were created with indicator kriging taking 50 mg nitrate dm^{-3} (critical concentration in drinking water) as threshold value. Nitrate concentrations for a given soil, management type, and year are based on the total leached nitrate dissolved in the precipitation surplus. This concentration is compared with the threshold value. Figure 2.11 illustrates how models can be used to quantify effects of nutrient management on production and environment.

Figure 2.12 shows six maps with water-limited yields (ton dry matter ha^{-1}) of potatoes for six years. The year 1988 did not show any clear pattern. We see that patterns for water-limited yield are comparable for the years 1989, 1990 and 1992-1994. The 1991 growing season started quite wet, which resulted in an inverse pattern where relatively high yields were obtained on sandy spots while yields in the more clayey spots were clearly depressed by oxygen deficiencies. Data in Figure 2.12 illustrate use of modeling to express variability of crop yield within a field, demonstrating the major impact of different weather conditions. The general

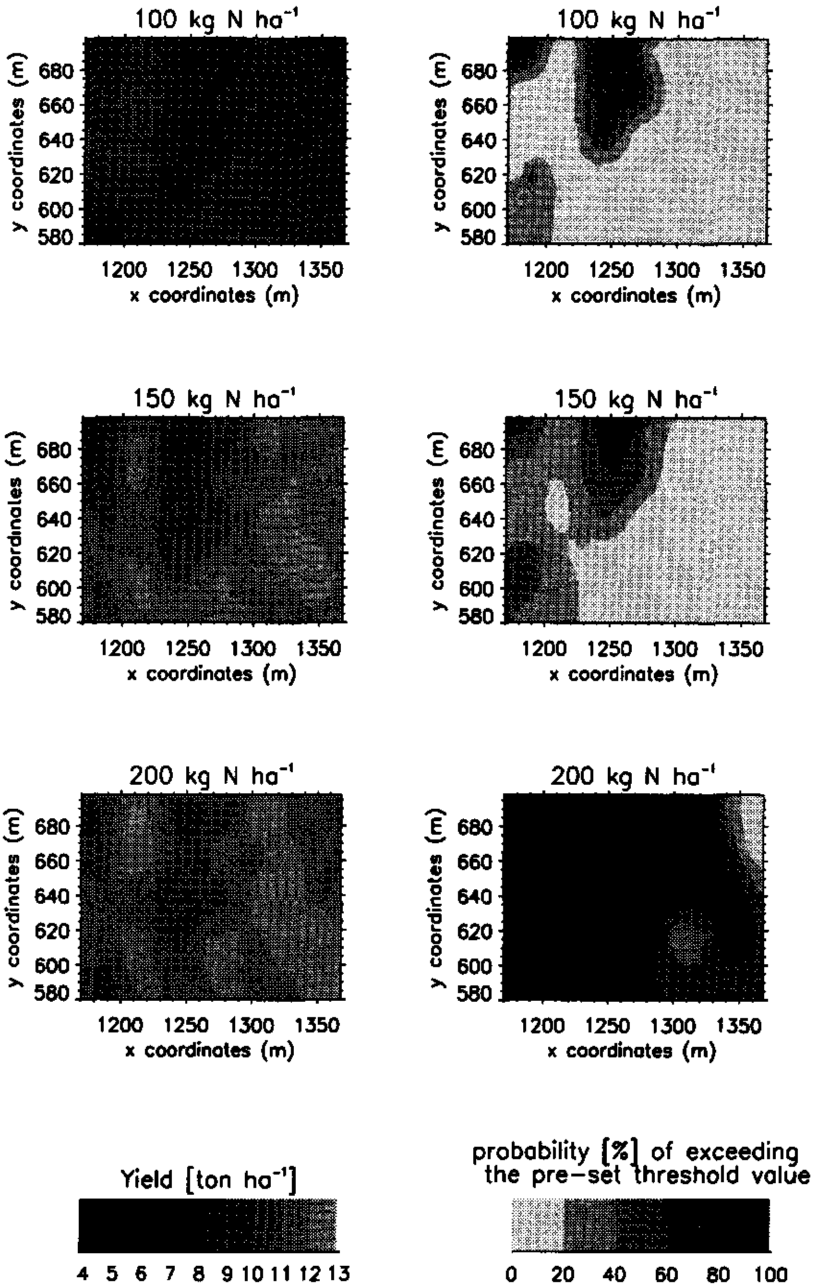

Figure 2.11: *An example on how models can be used to quantify effects of nutrient management on production levels and risk of environmental pollution. Yields at three fertilizer rates in 1994 are displayed in the left colom while in the right colom the corresponding probability that a threshold value for nitrate leaching is exceeded are shown.*

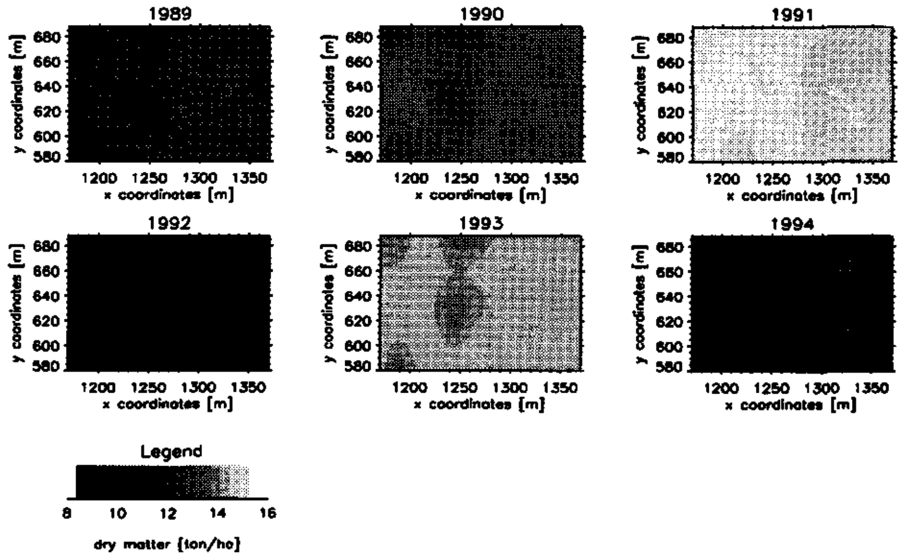

Figure 2.12: *Simulated water-limited production levels of potatoes for six years.*

or prototype pattern for the experimental field extracted from the simulated water limited yields is shown in Figure 2.13 as derived from Van Uffelen et al. (1997). This figure is an example of a basic management map that can be used for SSM. Generalizing modeling data. So far, point and area data have been considered for specific fields. Not only real conditions have been discussed, as characterized by monitoring, but also simulated conditions corresponding with weather conditions in different years. Such simulations are crucial to define patterns within the field which can form the basis for SSM measures. The type of measures and the operational procedures involved are not discussed here as they are beyond the scope of this particular paper. The character of procedures being discussed so far is rather exclusively focused on particular fields belonging to a given farm. We believe that a link with soil survey data bases, which are operational in many countries by now, would be profitable to increase the use efficiency of data obtained in a given field and to make soil survey data more relevant for modern applications.

Results obtained by point-simulations for different years for soils belonging to a given soil series can be stored in a database thereby expressing its variability. Simulation results can be expressed in terms of probability distributions as presented elsewhere by, e.g., Van Lanen et al. (1992).

Aside from considering soil series, the condition of the soil also should be considered. Soils, identical from a pedological point of view may differ significantly

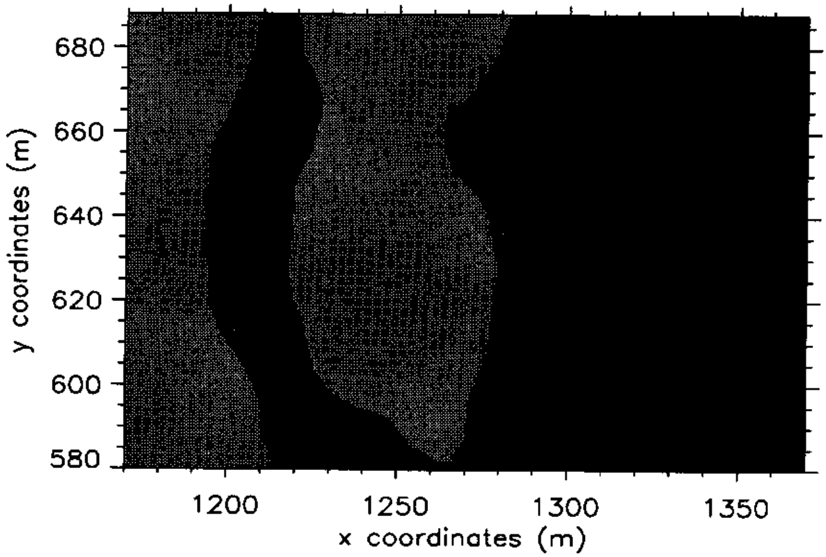

Figure 2.13: *Prototype pattern of a SSM map for the experimental field.*

from a functional point of view because of effects of soil management. Within the same soil series compacted soils may occur, soils with increased organic matter contents due to organic farming, and soils with depleted organic matter contents due to poor management. Earlier we suggested introducing "soil structural phases" for given soil series. (Wagenet et al., 1991; Bouma, 1992). These structural phases can be identified by field surveying of areas that are covered by a soil survey. By emphasizing soil structural conditions and organic matter contents, different "structure types" can be distinguished and simulation can be used to define dynamic land qualities such as moisture supply capacity, trafficability, workability etc. (e.g. Van Lanen et al., 1986, 1992). By linking each type to a particular type of soil management (e.g. conventional arable, biological, grassland, etc.) and the period during which this management has been applied (following possibly other types of management), we can obtain a characteristic "prototype", which is bound to be useful for practical recommendations. Bouma (1994) has referred to this prototype in terms of a "window of opportunity". A set of field experiments yielding comparable results is inconceivable because of time and money needed to do long-term research. With traditional soil surveys finished in many countries, it would be attractive to build on existing soil survey data and add data that are relevant for modern applications.

Conclusions

1. Modeling is a crucial activity to effectively characterize soil variability in space and time because field observations and measurements can never cover the range of conditions that are relevant for modern questions dealing with agricultural production and environmental quality which are central in site specific management.

2. However, field observations and measurements are crucial as well to allow proper calibration and validation of models. Measurements on soil water content, yield, soil nitrogen status and soil solution can be done using standard equipment. Availability of modern techniques (TDR, Remote Sensing, GPS, yield monitoring on-the-go) facilitates part of such measurements. However, field measurements of solute fluxes is not yet possible, and can therefore not be used for model calibration and validation. Fluxes are calculated by multiplying hydraulic gradients and hydraulic conductivities.

3. Modeling at point locations, to be followed by using interpolation techniques to extend point values to areas of land, has proven to be an effective procedure to express variability, also in terms of the error induced by parameters used in the modeling effort.

4. A plea is made to incorporate modeling data in existing soil survey databases for defined soil series, distinguishing different structural phases as a result of different types of soil management. Each soil series thus offers a specific "Window of opportunity".

Chapter 3

Spatial variability: implications for farm management

3.1 Identification of management units based on stable soil related yield patterns [3].

Abstract

Site specific management (SSM) aims to maximise crop production and make efficient use of agrochemicals. This is achieved by varying farm management practices considering local variability. Maps displaying relevant soil variability are needed to guide these site specific practices. As it takes years to collect yield and leaching data to produce maps, use of simulation models is recommended to produce yield and leaching patterns. Based on 65 well documented locations on a 2.5 ha field, simulations of potato growth were made for seven years, assuming a water-limited production situation. From these point simulations crop development patterns are derived using kriging techniques. For site specific management we need to determine areas with relatively uniform behaviour in different years. A pattern-comparison technique, based on taxonomic distances between patterns among the seven years, was modified and used to determine a prototype pattern. This prototype pattern is considered to be the basis for a SSM map.

[3] *published as:* Van Uffelen C. G. R., Verhagen, J. and Bouma, J. 1997. Comparison of simulated crop yield patterns for site specific management. Agricultural Systems, 54:207 – 222

Introduction

Farming treatments are currently applied uniformly at the field scale, ignoring variability of soil- and crop conditions within the field. Until recently, documentation of yield and soil variability at field scale was difficult but with the advance of global positioning systems (GPS) and on-the-go yield measurement there is increasing evidence that this variability is highly significant as it often amounts to a factor of three or four among subplots (Birrel et al., 1995; Verhagen et al., 1995b). Reasons for this variation can be many, such as e.g. differences in soil fertility and soil structure and local occurrence of pests and diseases. Once reasons have been identified, corrective measures can be taken, using equipment that allows site-specific management practices. Site specific management (SSM) often results in a reduction of costs and higher crop yields while leaching of agrochemicals is reduced (Van Noodwijk and Wadman, 1992; Reetz and Fixen, 1995; Booltink and Verhagen, 1997). So far economic benefits are only based on higher yields and reduced costs for the farmer while positive effects of reduced leaching of agrochemicals cannot yet be expressed in economic terms.

Maps of fields are needed to guide SSM equipment as long as sensor techniques have not become operational. To manage within-field variability, areas displaying similar behaviour (stable patterns), with respect to a certain characteristic (e.g. yield potential, leaching potential), in different years have to be identified. Yield maps provide information on the integrated effects of the physical, chemical and biological processes under certain weather conditions for a given crop. To distinguish between the different sources of variability is crucial when we aim to react to variable conditions. Therefore we need to understand basic processes contributing to the variability. Thus, yield maps can provide no clear guidelines if no additional information on eg. variability on soil physical and chemical properties or information on pest and diseases are provided. Also the variability of weather may explain part of the variability for that particular year and crop.

An alternative is the use of calibrated and validated simulation models for crop growth and nutrient fluxes, which have been developed in the last decades (e.g. Teng and Penning de Vries, 1992). Simulation models are useful tools for a systematic analyses of dynamic systems and can play an important role in understanding the described processes and their interactions. A mechanistic deterministic simulation model was used in this study to calculate water-limited yields of potatoes for different years following the methodology of Verhagen et al. (1995a). Water limited yields focus on the effects of shortages or excess of water on production, assuming that nutrient supply is non-limiting and pests and diseases do not occur. This approach is taken because irrigation needs can directly be derived from the simulation results and moreover N requirements can be estimated from biomass production levels (Neeteson and Wadman, 1987). Yield patterns for different years obtained from simulations can be compared and generalized to produce a map for a particular field showing subareas that behave consistently different and have different input needs. The purpose of this study was, therefore, to develop a method to obtain a generalised map which can be used for SSM.

Materials and methods

Soils

The study area is a 2.5 ha field of an experimental farm in the Wieringermeer polder in the northwestern part of the Netherlands. Before reclamation in 1930, the experimental farm was part of a tidal mudflat. Because of the dynamic sedimentation environment, both horizontal and vertical soil-spatial variability are high. The soils are strongly layered with textures ranging from sand to silty clay. The individual texture lenses vary in thickness from 1 mm to 50 mm. During a previous survey on the same farm, soils were classified as fine-loamy, calcareous, mesic Typic Udifluvents (Finke and Bosma, 1993).

The complex nature of the soil imposes complications when computing water and nutrient fluxes. Apart from the required computer power needed to perform the calculations for these multi-layered profiles, collection of the basic data would be impossible using a standard soil auger. Finke and Bosma (1993) and Verhagen et al. (1995b) used the functional-layer concept (Wösten et al., 1986) to generalize the stratified layers into a limited number of functional layers. A functional layer is a soil layer having significantly different hydrological properties as compared to other layers. Four functional layers were identified. For each individual functional layer a number of soil physical measurements were made. The crust method (Booltink et al., 1991) was used to measure the hydraulic conductivity at near saturation. The retention and hydraulic conductivity curves at higher suctions were derived using the multi-step outflow method (Van Dam et al., 1994). For each functional layer average retention and hydraulic conductivity curves are obtained by geometrically averaging five measured curves. Average hydraulic conductivity and moisture retention data of the four functional layers are shown in figure 3.1. The soils in the area are described using the four functional layers. Each augering is described as a sequence of functional layers with varying thickness. The hydrologic characteristics of the functional layers are basic input in dynamic simulation models.

Sampling grid

Webster and Oliver (1990) state that most precise estimates are obtained from surveys on regular grids. The soil data in the experimental plot were collected

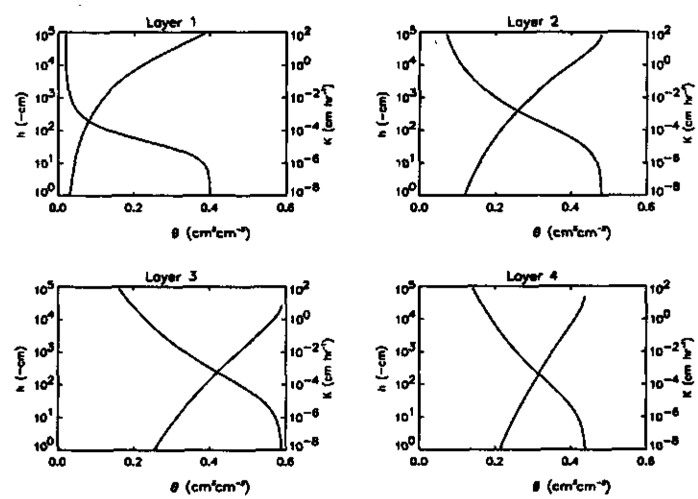

Figure 3.1: *Average moisture retention and hydraulic conductivity data for the four functional layers, h is the matrix potential and K is the hydraulic conductivity.*

using a regular sampling grid of 25 m, supported by some short distance, 5 m, information. This design was also used for the yield mapping (Figure 3.2).

Simulations

The simulation of the soil-crop system used the dynamic simulation model WAVE (Water and Agrochemicals in soil and Vadose Environment, Vanclooster et al. 1994). WAVE integrates existing models, including dynamic simulations of water flow based on the SWATRER-model (Dierckx et al., 1986) and a SUCROS type crop growth model (Spitters et al., 1988). In this study only water limited yields are calculated disregarding the effect of nitrogen stress on crop production. Water stress is calculated according to Feddes et al. (1978), in which the maximum water uptake is defined as a function of depth. The total water uptake is the integral over the root zone. Water uptake is reduced at high and at low water potentials, owing to water excess and shortage respectively.

Spatial interpolation

Interpolation between point simulations was made using ordinary kriging. Kriging is 'a collection of generalized linear regression techniques for minimizing an estimation variance defined from a prior model for a covariance' (Olea, 1991). It is a local estimation technique which provides the best linear unbiased estimator

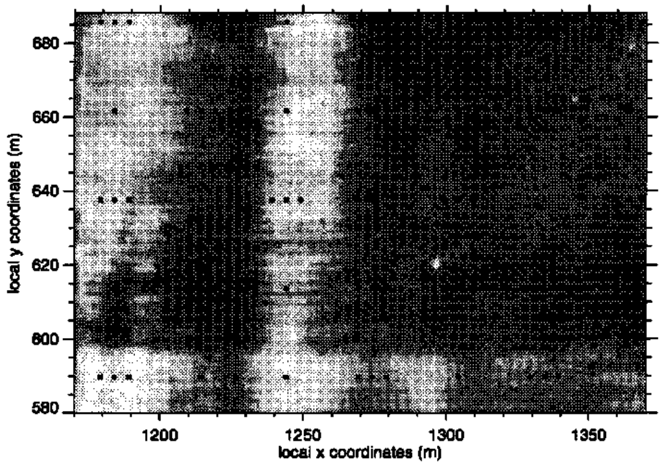

Figure 3.2: *Layout of sampling design superimposed on an aerial photograph of the bare soil at the experimental field. The light colored areas mark the sandy parts.*

of the unkown characteristic only requiring the covariance or variogram (Journel and Huijbergts, 1978). The (semi)variogram expresses the degree of spatial dependency or semivariance between point observations as a function of the distance or lag (h) between points.

Kriging and semivariogram analyses were made using GSLIB (Geostatistical Software Library, Deutsch and Journel 1992) and WLSFIT (Weighted Least Squares FIT, Heuvelink 1993) which were embedded in Interactive Data Language (IDL, Version 3.6.1a) routines. The goodness of fit of the variogram is determined by the ratio sum of squares due to deviations and total sum of squares SS_D /SS_T. Perfect fit is obtained when this ratio is zero, on a scale from zero to one.

Determination of local similarities

Spatial interpolation results in a spatial pattern represented by a mesh of estimated values. To be able to compare two different patterns $n (n = 1, 2)$, the values at the nodes xy of the meshes, $v_{n,xy}$ are converted to their standard normal form, $z_{n,xy}$:

$$z_{n,xy} = \frac{v_{n,xy} - \overline{v}_n}{s_n} \tag{3.1}$$

in which $\overline{v}_n$ is the average value and s_n the standard deviation of the original values in pattern n. In this way, the patterns are expressed in dimensionless units.

The principle of the pattern comparison method is to traverse the mesh with a so-called window, which is a smaller mesh that compares corresponding portions of the larger patterns. Starting in the upper left corner of the patterns to be compared, a window of e.g. five by five nodes on two patterns is compared according to the procedure described below. After storing the result of this comparison in a new mesh representing the spatial similarity, the window shifts one column, taking again 25 nodes of which 20 were also used in the first comparison. In this study the size of five by five nodes is taken, to approximate the scale at which the farmer can adjust his tillage operations.

The procedure for a window on two patterns is as follows. A small portion of the pattern $n = 1$ is copied into the window. The pattern in the window, $z_{win,xy}$, is approximated by:

$$\begin{aligned} z_{win,xy} = b_{n,0} + b_{n,1} \times x_{win} + b_{n,2} \times y_{win} + b_{n,3} \times x^2_{win} \\ +b_{n,4} \times y^2_{win} + b_{n,5} \times xy_{win} + b_{n,6} \times x^3_{win} \\ +b_{n,7} \times y^3_{win} + b_{n,8} \times x^2 y_{win} + b_{n,9} \times xy^2_{win} \end{aligned} \quad (3.2)$$

The coefficients $b_{n,0} - b_{n,9}$ represent the effect of the respective polynomial term on the shape of the pattern in the window. These coefficients are calculated by means of the least squares method. The same procedure will be repeated for pattern $n = 2$, copying the corresponding part of the pattern into the window. The number of coefficients and the number of nodes in the window determine the amount of detail to be considered. One has to adjust these characteristics to cope with the considered problem.

So far, the comparison of a window on two patterns has resulted in two sets of coefficients, $b_{n,0} - b_{n,9}$ for $n = 1, 2$. Davis (1986) proposes measures of similarity for the polynomial description of patterns. One useful measure is the taxonomic distance d, which can also be used to compare the polynomial description of a window on two patterns. Introducing p as the number of polynomials used ($p = 10$), the definition reads:

$$d = \sqrt{\sum_{i=0}^{p-1} \frac{(b_{1,i} - b_{2,i})^2}{p}} \quad (3.3)$$

In the definition of the taxonomic distance, all coefficients have got the same impact on the value of d. This can be distorting the real impact of especially the high order terms. Depending on the size of the window, a cubic term with a small coefficient can have more impact than a linear term with a larger coefficient, although according to the definition of d, the latter coefficient seems to be more important. Therefore in this study the following modification is proposed and referred to as the weighted taxonomic distance

$$d_w = \sqrt{\sum_{i=0}^{p-1} \frac{(w_i(b_{1,i} - b_{2,i})^2)}{\sum_{i=0}^{p-1} w_i}} \tag{3.4}$$

in which w_i is a weight equal to the range along the z-axis for the corresponding polynomial term i. This weight is only a function of window size and mesh distance.

Perfect matching fits are obtained when d_w equals zero. A window on increasing dissimilar patterns results in increasingly greater taxonomic distances. The value of d_w is not constrained by an upper limit.

When calculating d_w-values for a traversing window on two patterns, a new pattern of the same dimensions as the original patterns is created, because the calculated weighted taxonomic distance will be applied to the centre of the present location of the window. The edges of this similarity pattern do not get d_w-values. This new pattern represents the local similarity of two patterns. An IDL routine has been written that displays two patterns as surface plots, in which the colour of the surface indicates the value of the local degree of similarity. This is a powerful tool in identifying differences in patterns. Studying the combination of both patterns and the superimposed d_w-values, it is relatively easy to identify the threshold d_w-value that separates similar parts from dissimilar parts. The value of this threshold is dependent on the scope of the problem. Once a d_w-value is established for certain types of patterns, this value remains constant.

Determination of the overall similarity and prototype pattern

The overall similarity of two patterns can be calculated as the average weighted taxonomic distance $\overline{d}_w$, which is the sum of the d_w values in the similarity pattern divided by the number of d_w-values. This definition allows one to get insight in similarities of groups of e.g. harvest patterns during some years by creating a so-called similarity matrix in which the average weighted taxonomic distance is calculated between the different years.

The prototype pattern is the basis for the generation of the SSM-map. It is identified by means of the cumulative $\overline{d}_w$-value. This is the sum of the $\overline{d}_w$-values between a pattern and the remaining patterns in a series of observations. The cumulative $\overline{d}_w$-values have to be calculated for all patterns in a series. The pattern having the lowest $\overline{d}_w$-value will be the prototype pattern.

Results and discussion

Model validation

Initialization of the WAVE model requires a large number of parameters. The parameters used in this study were taken from field observations or were taken from publications. During the growing season of 1994 a potato crop (cv. Saturna) was grown, basic crop data needed for the SUCROS model was taken from Spitters et al. (1988). The determined hydraulic functions (see section on soil) were used as basic input in the water model SWATRER. Bottom and top boundary conditions were measured during the growing season, only incoming radiation measurements were not available and were taken from a nearby (50 km) climate observation station. The uptake of water is restricted under certain conditions, too wet and too dry conditions resulting in reduction of growth. Stress as a result of unfavourable pressure heads is defined as a dimensionless sink term. Optimal water uptake is defined as occurring between -50 cm H_2O and -1000 cm H_2O, for the high pressure head a value of -10 cm H_2O was taken (Diels, 1994). The wilting point was set at -8000 cm H_2O based on crop specific information, (Rassenlijst, 1995; Spitters and Schapendonk, 1990).

The water balance was validated for the 1994 growing season. The water content was measured biweekly using TDR probes at 30 locations at several depths. Simulation results obtained with the averaged moisture retention and hydraulic conductivity curves are shown in figure 3.3, R^2 is 0.65.

Model runs

Simulations for two scenarios were executed. In the first one a fixed date of crop emergence and harvesting was used (respectively May 27^{th} and September 12^{th}). In the second scenario the planting date was determined by considering the first date of adequate trafficability of the field. Because the second scenario introduces elements not considered in this text, the results of the first scenario are presented.

Spatial interpolation

Table 3.1 shows the main characteristics of the semivariograms that were calculated for the yield patterns of 1989 - 1994. In all cases the spherical model yielded the best (or equivalent to the gaussian model) SS_D SS_T ratios. The spherical model is defined as:

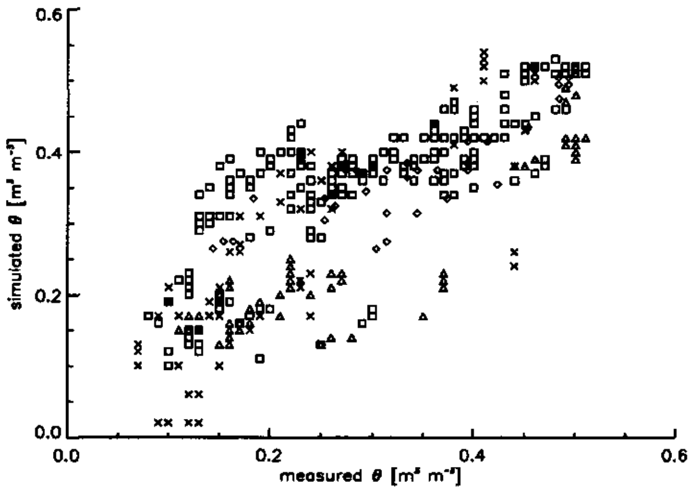

Figure 3.3: ***Simulated versus measured moisture content at several depths.*** ◇ ***indicate observations from 0 - 40 cm depth,*** □ ***40 - 60 cm.,*** △ ***60 - 80 cm and*** × ***marks observations at 80 - 90 cm depth.***

$$\gamma = c \times \left(\frac{3h}{2a} - \left(\frac{h}{a} \right)^3 \right) \text{ if } h \leq a \qquad (3.5)$$
$$= c \text{ if } h > a$$

in which γ is the semivariance, h the lag distance, a the range, and c the sill. A nugget is added to this model. It is necessary to use the same semivariogram model for all patterns which have to be compared to each other, to prevent pattern dissimilarity as a result of different semivariogram models. In 1988 no spa-

Table 3.1: ***Characteristics of calculated spherical semivariograms of spatial yield data for 1989 - 1994.***

Year	*SS_D/SS_T*	*Nugget*	*Sill*	*Range*
1989	*0.06*	*0.00021*	*0.0011*	*243*
1990	*0.24*	*0.048*	*0.19*	*48.7*
1991	*0.71*	*0.0089*	*0.0068*	*46.8*
1992	*0.17*	*0.0051*	*0.035*	*48.0*
1993	*0.25*	*0.0016*	*0.034*	*46.9*
1994	*0.08*	*0.37*	*0.92*	*59.3*

tial differences were found which is considered to result from potential growing conditions on the entire field. The semivariograms are fitted on basis of six lag interfalls of 20 m each (the first interval is 10 m). The quality of the fits by the semivariogram model are reasonably well to very good, except for the fit of 1991. Table 3.2 shows the characteristics of the spherical semivariogram fits for potato development during 1991. It is clear that up to August 15^{th} the fit is very good whereafter the quality decreases.

Pattern comparison

Figure 3.4 shows the yield patterns for the years 1989 - 1994. As was stated before, potato development during 1988 resulted in a flat pattern (yield is 12.2 tons dry matter per hectare). Most patterns show a decrease in yield around location (1250, 620). This is a sandy part in the field at which water stress occurs most rapidly. An exception to this behaviour occurs in 1989 when the yield pattern is inverted: The highest yield occurs in the sandy area, although absolute differences are very small. The reason for pattern inversion is occurrence of rather wet weather conditions. The sandy area is able to drain the surplus of water more rapidly than the more clayey area.

Table 3.3 lists the average weighted taxonomic distances which indicate the overall similarity of the potato-yield patterns. These values can be used to identify patterns which lack similarity: Pattern inversion results in the highest $\bar{d}_w$-values.

Spatial differences in yield are only for some years of economic interest. This holds for 1990 and 1994, where differences in simulated minimum and maximum yield are respectively 1.43 and 3.32 tons dry matter per hectare. Simulations describe ideal situations in which only water stress is taken into account.

Simulating potato-yield for seven years yielded three patterns. For most years (1990-1994), the sandy parts have lowest yields. For 1988, no differences were simulated. For 1989, the pattern which was found for 1990-1994 is inverted, as

Table 3.2: *Characteristics of calculated spherical semivariograms of spatial potato development data during 1991.*

Date	*SS_D/SS_T*	*Nugget*	*Sill*	*Range*
6-30	*0.03*	*4e-5*	*0.0003*	*243*
7-15	*0.05*	*6e-5*	*0.0003*	*243*
7-30	*0.03*	*6e-5*	*0.0004*	*243*
8-15	*0.04*	*0.0001*	*0.0006*	*243*
8-30	*0.64*	*0.0025*	*0.0021*	*45.5*
9-11	*0.71*	*0.0089*	*0.0068*	*46.8*

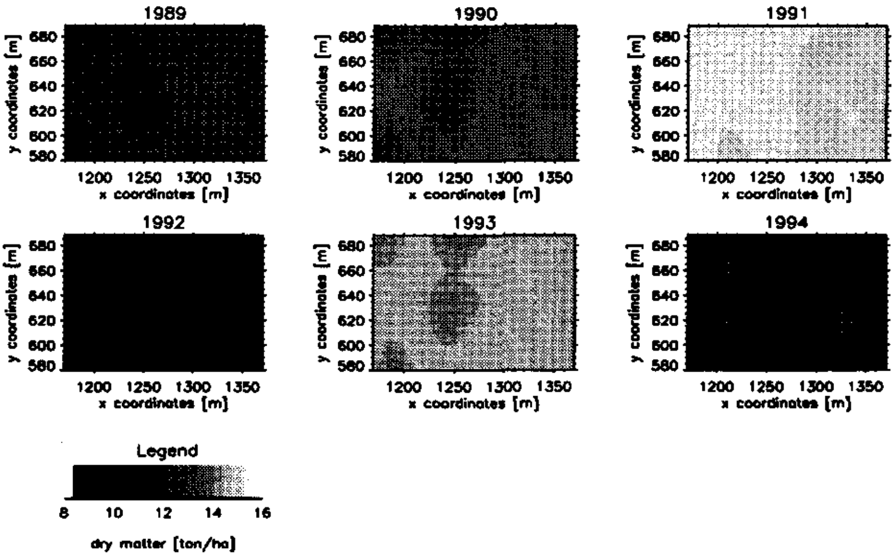

Figure 3.4: *Contour plots of yield patterns for 1989 - 1994. (1988 has got no pattern.) Contours delineate yield in tons dry matter* ha^{-1}.

the sandy parts have the highest yields.

The yield-pattern in 1988 is the result of potential growing conditions. This is almost the case in 1989 as well, only heavy rains on 9 July (41.9 mm), preceded by 37 mm of rain from 28 June until 2 July, resulted in wet conditions on the more clayey parts of the field, resulting eventually in small yield differences. The remaining patterns can be explained by the relatively low water-holding capacity in the sandy parts of the field, which results in water stress after only short periods without precipitation.

It is also possible to follow the patterns as they develop during one crop cycle. For all years, simulated patterns of the weight of the tubers were determined for 15 and 30 June, 15 and 30 July, 15 and 30 August and 11 September. In most cases, after initiation of a pattern because of water stress in part of the field, the pattern does not change anymore. But the pattern usually gets more pronounced during development. The only exception is 1991. According to table 3.4 there is a distinct difference between the patterns before 30 August, and the last two patterns. Before 30 August the crop on the more clayey parts of the field slightly suffered from wet conditions, but between August 15 and 30 the dominant patterns of the other years appears.

Map generation

Decisions in agriculture are based on area information. Site specific management aims to adjust management for uniform areas within farm fields. For site specific management we need to determine areas with more or less uniform behaviour. The cumulative $\overline{d}_w$-value is considered here as a measure of similarity. From table 3.3 we can extract the most dominant patterns. In our case this is the pattern as developed in 1990, 1992 and 1993. These are very similar, according to the weighted taxonomic distances between them. As a result of this, it is an arbitrary decision which pattern of the three to choose. We will take the 1993 pattern as prototype pattern for map generation. We take this dominant pattern as a prototype pattern for site specific management.

For 1993 the maximum yield was 14.07 tons dry matter per hectare and the minimum yield was 13.44 tons, indicating a yield gap of 0.63 tons. The maximum yield, in this case, is equal to potential yield. Lower yields can be explained by growth reduction as result of water deficiency. Irrigation can sometimes compensate for this water related stress.

The identification of areas to be irrigated is made by selecting a cut-off value. The farm field is divided into uniform management units by taking as cut-off value:

$$\text{cut-off} = \text{Yield}_{min} - 0.75 \times (\text{Yield}_{max} - \text{Yield}_{min}) \qquad (3.6)$$

In which Yield_{min} and Yield_{max} are minimum and maximum yield respectively. Areas with yields below this value are areas showing relevant water stress. The choice of the cut-off value should be based on an economic analysis but because of lack of basic economic data in our study, the cut-off value is chosen arbitrarily. Result of the analysis is a site specific irrigation map for the study

Table 3.3: *Average weighted taxonomic distances between the yield patterns of 1989 to 1994. These values indicate the similarity of the simulated yield patterns. Larger values indicate increasing lack of similarity.*

	1989	*1990*	*1991*	*1992*	*1993*	*1994*	*Sum*
1989	*0*	*0.004*	*0.004*	*0.004*	*0.004*	*0.004*	*0.020*
1990		*0*	*0.002*	*0.001*	*0.001*	*0.002*	*0.010*
1991			*0*	*0.002*	*0.002*	*0.003*	*0.011*
1992				*0*	*0.001*	*0.002*	*0.010*
1993					*0*	*0.002*	*0.010*
1994						*0*	*0.013*

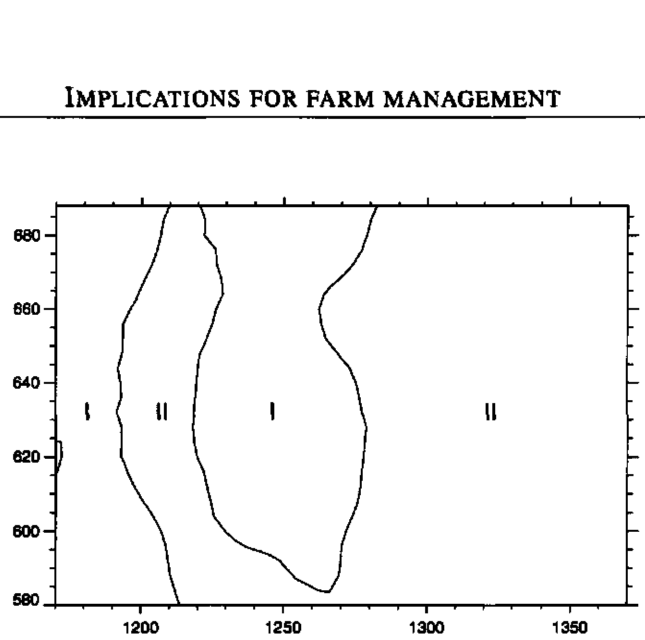

Figure 3.5: *Proposed site specific management map. Area I is the high imput area, area II is the low input area.*

area in which two areas are indicated (figure 3.5): I. is the unit that should be irrigated and II. the unit that need not be irrigated. The distinction is made using the selected cut-off value.

Conclusions

1. The weighted taxonomic distance is a measure of similarity among different maps of the same area which can be used to analyze spatial patterns.

2. Similarities between simulated crop yield patterns within and between dif-

Table 3.4: *Average weighted taxonomic distances between the the potato development patterns during 1991. These values indicate the similarity of the simulated yield patterns. Larger values indicate increasing lack of similarity.*

	30/6	*15/7*	*30/7*	*15/8*	*30/8*	*11/9*	*Sum*
30/6	*0*	*0.000*	*0.000*	*0.000*	*0.004*	*0.004*	*0.008*
15/6		*0*	*0.000*	*0.000*	*0.004*	*0.004*	*0.008*
30/7			*0*	*0.000*	*0.004*	*0.004*	*0.008*
15/8				*0*	*0.004*	*0.004*	*0.008*
30/8					*0*	*0.001*	*0.017*
11/9						*0*	*0.017*

ferent growing seasons can be quantified.

3. Yield differences within fields are important for farm management. Maps for site specific management can be derived through pattern analysis, based on simulations of crop yields, as was demonstrated in this study.

3.2 Comparing traditional with site specific N fertiliser practices in the dry season [4]

Abstract

The effects of site-specific N fertiliser recommendations on potato yield and leaching of nitrate were studied for a farm field in the Netherlands. A validated process based dynamic simulation model was used to calculate potato yields and leaching of nitrate for seven fertiliser doses on 65 locations during 1994. Results of the simulations are discussed using the distribution function and interpolated spatial patterns. The leaching risk was analysed by comparing cumulative nitrate leaching concentrations with a pre-set threshold value based on government regulations for drinking water. The current recommended fertiliser rate was 250 kg N ha^{-1} (R-scenario). Two site-specific fertiliser scenarios were defined: one scenario based on seven fertiliser doses (S-scenario) and the other scenario based on seven years of simulated water limited yield (B-scenario). The R-scenario resulted in an average yield of 11.57 t dry matter ha^{-1} and a nitrate leaching quantity of 95.9 kg nitrate ha^{-1} for 1994. Both site-specific fertiliser scenarios resulted in a lower average yield. Calculated average yield was 11.13 t dry matter ha^{-1} for the S-scenario and 11.29 t dry matter ha^{-1} for the B-scenario. Nitrate leaching was reduced by 2.4 to 39.3 kg nitrate ha^{-1} for the S-scenario and 39.7 kg nitrate ha^{-1} for the B-scenario.

[4] *in press:* Verhagen J. 1997. Site specific fertiliser application for potato production and effects on N-leaching using dynamic simulation modelling. Agriculture, Ecosystems & Environment.

Introduction

Farm fields are not homogeneous and crop production is therefore often quite heterogeneous. Crop development may differ locally as a result of different soil types, soil fertility, local compaction or other factors resulting from farm management.

Reacting to spatially variable conditions, "precision agriculture" aims to maximize crop production while minimising use and leaching of agrochemicals. A good understanding of key processes in the soil-crop system is essential to develop precision agriculture.

Dynamic simulation models are important tools in identifying and describing key processes in the soil-crop ecosystem (e.g. Verhagen et al., 1995a). Moreover, validated simulation models provide the opportunity to extend the scope of field experiments beyond the experiment itself. By running models for different weather data and/or farm management practices, knowledge is accumulated on the dynamic behaviour of the system. This knowledge, combined with expert knowledge, is the basis for precision agriculture.

In this study the effects on nitrate leaching and potato production from regular and site-specific fertiliser application were compared using a validated simulation model. The connection between leaching and production is debatable because leaching is mainly confined to the wet autumn/winter period succeeding the growing season. So when calculating production and leaching for one year the interpretation of the results is mainly limited by the climatological boundary conditions of that particular year. The system studied did not include tillage measurements of catch crops, aimed at reducing nitrate leaching.

Materials and methods

Soils

The soils in the area are classified as fine-loamy, calcareous, mesic Typic Udifluvents (Soil Survey Staff, 1975). Soil variability is high because relatively large textural differences are observed over short distances (Finke and Bosma, 1993; Verhagen et al., 1995a). Each individual soil profile is characterised by functional layers as described by Verhagen et al. (1995a), (Figure 3.6 and Table 3.5). Each soil profile is described in terms of a sequence of functional layers with varying thicknesses.

Spatial soil variability of the farm field was characterised using 65 augerings on a regular grid including short distance observations to allow geostatistical analyses. Figure 3.7 presents a cross section of the central transect which clearly

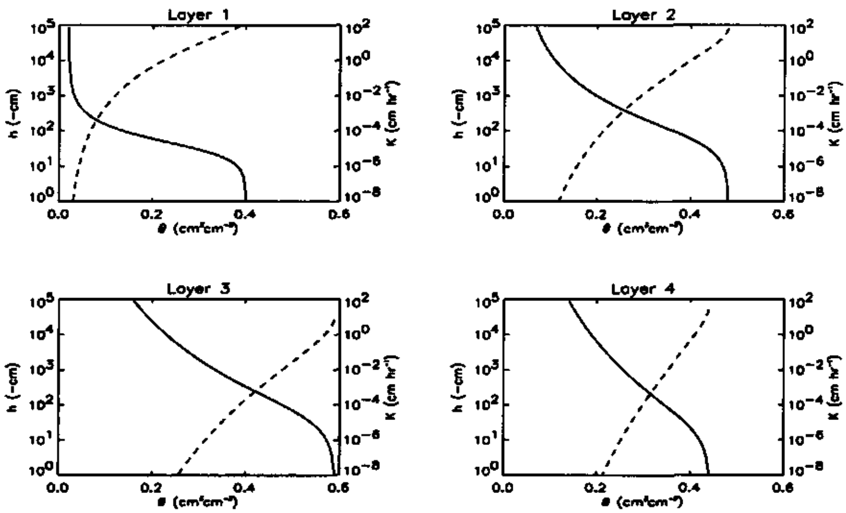

Figure 3.6: *Average retention and conductivity curves for the four functional layers. Averages are based on a minimum of 5 measurements per layer.*

shows the change from the sandy profiles at the left side of the field to the loamy and clayey profiles at the right part of the field. This sequence is a general characteristic of the field.

Monitoring

During the growing season precipitation and temperature were measured in the direct of the field. Global radiation data was obtained from a nearby climatic station.

Soil moisture was monitored using Time Domain Reflectometry (TDR) equipment biweekly during the growing season at 30 locations. Mineral N was sampled at eleven locations just after planting and just after harvesting the potato crop. These data together with the final yield data were used to calibrate the simulation model for the 1994 growing season.

Simulation model

Simulation of the soil-crop system was realised by using the dynamic simulation model WAVE (Water and Agrochemicals in soil and Vadose Environment, Vanclooster et al. 1994). WAVE integrates four existing models, including dynamic

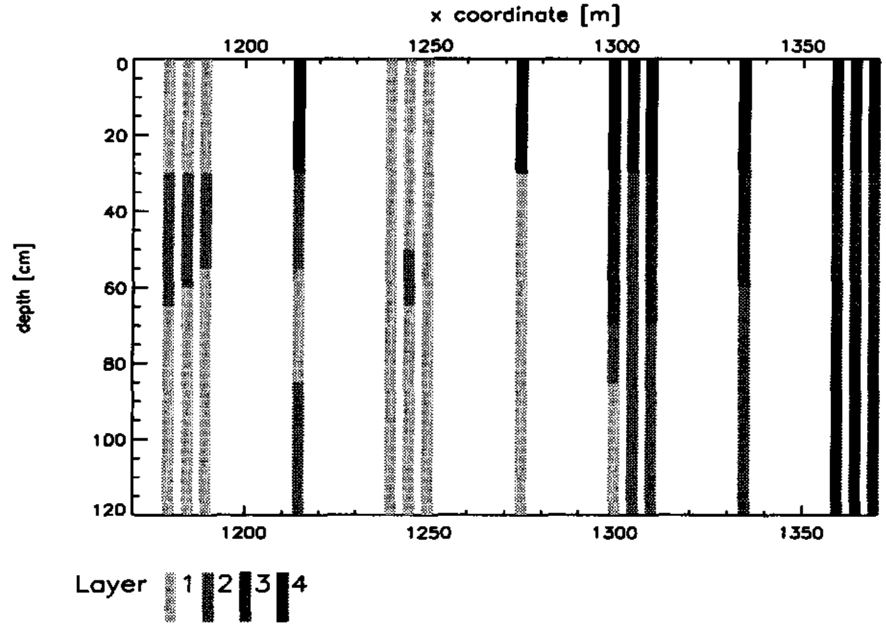

Figure 3.7: *Cross section of the central transect.*

simulation of water flow based on the SWATRER model (Dierckx et al., 1986), a nitrogen model based on the SOILN-model (Bergström et al., 1991), a heat and solute transport model based on the LEACHN-model (Hutson and Wagenet, 1992) and the SUCROS crop growth model (Spitters et al., 1988). Two conceptual changes to the original WAVE model were made. First, in the revised version the total water uptake is the integral over the root zone, although water uptake by plant roots was originally modelled assuming preferential uptake at the top compartments excluding roots in deeper layers. Second, the nitrogen uptake was originally modelled

Table 3.5: *Basic soil data for the four functional layers. is the bulk density [kg dm^{-3}], K_{sat} is the saturated hydraulic conductivity and θ_{sat} is the saturated water content [m^3 m^{-3}]*

Layer	ρ [kg dm^{-3}]	(sd)	Org. matter %	Clay %	K_{sat} [cm day^{-1}]	θ_{sat}	(sd)
F1	1.48	(0.039)	0-2	0-4	183	0.40	(0.02)
F2	1.21	(0.079)	0-2	4-11	128	0.48	(0.04)
F3	1.08	(0.231)	0-2	11-23	36	0.59	(0.06)
F4	1.30	(0.045)	0-3	4-23	265	0.44	(0.08)

using the nitrogen concentration in the leaves as driving variable. In the revised version, nitrogen uptake is linked to biomass production as described below.

Water stress is calculated according to Feddes et al. (1978), in which the maximum water uptake is defined by a sink term as a function of depth. Water uptake is reduced at characteristic high and low pressure head values. Optimal water uptake is defined between -50 cm H_2O and -1000 cm H_2O, for the high pressure head a value of -10 cm H_2O was taken (Diels, 1994). The wilting point was set at -8000 cm H_2O based on crop specific information, (Rassenlijst, 1995; Spitters and Schapendonk, 1990).

Stress resulting from nitrogen deficiencies is calculated using the "critical nitrogen concentrations" as defined by Greenwood and coworkers (Greenwood et al., 1985, 1990). The relation used in the potato model is defined as:

$$N_c = 1.35 + 4.05 \times e^{-0.26 \times W} \tag{3.7}$$

in which N_c is the critical nitrogen concentration [%] and W the total weight [t dry matter ha^{-1}], describing the decrease in N percentage with increasing plant mass. The supply side is by convective and diffusive uptake. When the actual uptake is insufficient to sustain the necessary concentration as defined by equation 3.7, biomass production is proportionally reduced in response to the ratio of the actual and required uptake.

Fertiliser scenarios

Fertiliser recommendations in the Netherlands are based upon nitrogen content in early spring. These recommendations were established some 20 years ago using plot experiments and aimed to provide maximum yields with low risk. Apart from the soil N content rooting depth is also taken into account. The fertiliser recommendation for potatoes is defined as:

$$F_r = 285 - 1.1 \times N_{min} \tag{3.8}$$

in which F_r is the recommended fertiliser application [kg ha^{-1}] and N_{min} the mineral nitrogen content [kg ha^{-1}] over the top 60 cm, which is considered to be the average rooting depth for potato. The fertiliser is then spread evenly over the field ignoring spatial differences.

In early February, soil samples were taken by the farm manager and were sent to the National Soil Laboratory in Oosterbeek to assess the mineral N status. The average nitrogen concentration over the top 60 cm. was 35 kg ha^{-1}. Using equation 3.8 this would imply that a fertiliser application of 247 kg ha^{-1} is required.

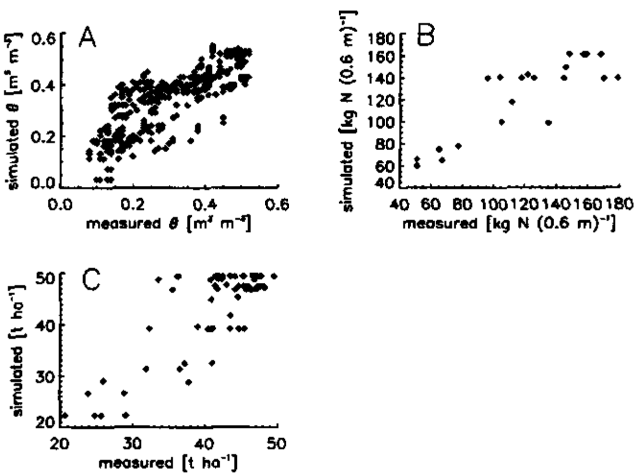

Figure 3.8: *Validation of the model. (A) watercontent (R^2 0.65), (B) mineral nitrogen [0-60 cm] (R^2 0.58) and (C) End Yield (R^2 0.65)*

The actual fertiliser application in 1994 was split into two applications and the total amount was based upon expert knowledge of the farm manager. The first application (18 February) was 156 kg N ha^{-1} and the second (June 23) was 40 kg N ha^{-1}.

The revised WAVE model was used to explore the effects of a series of fertiliser scenarios in order to assess relationships between fertiliser application, yield and nitrate leaching concentration. The starting point of the scenarios is the recommended fertilizer application (250 kg N ha^{-1}) and then decreased 200, 175, 150, 125, 100 and 50 kg N ha^{-1}.

The wet period between the first fertiliser application on February 18 and crop emergence on 27 May, resulted in high leaching, especially for the sandy soils. The date of the single application scenarios in the calculations was therefore set at one week before emergence to maximise benefit for the potato crop. The choice of this fertilising date was based on earlier studies made by Booltink and Verhagen (1997).

Evaluation procedure

By government regulation the nitrate concentration of drinking water may not exceed 50 mg NO_3 dm^{-3} (11.3 mg N dm^{-3}). Nitrate leaching patterns were assessed by considering this critical nitrate concentration as a cut-off value for nitrate discharge into the groundwater. The nitrate concentration is obtained by dividing the total amount of leached nitrate during the year by the total amount of leached water. Because the latter quantity differs among the years the total amount of nitrate allowed to leach also changes. For 1994 a maximum loss of 45 kg ha^{-1} nitrate is allowed. Cumulative nitrate load at one meter depth, just above the average groundwater table during the autumn/winter period, is regarded as lost to the groundwater.

Simulated yields and nitrate concentrations are discussed using cumulative distribution functions. To interpret simulated yields and nitrate concentrations on a spatial rather than on a point level, the 65 point simulations were interpolated using standard geostatical techniques. Yield patterns are generated using ordinary kriging allowing spatial comparison of yield patterns between the seven scenarios. Indicator kriging is used to assess spatially the probability that the cumulative nitrate concentration exceeds the pre-set threshold value. Kriging is a local estimation technique which provides the best linear unbiased estimator of the unknown characteristic only requiring the covariance or variogram (Journel and Huijbergts, 1978). The (semi)variogram expresses the degree of spatial dependency or semivariance between point observations as a function of the distance or lag (h) between points. Ordinary kriging, indicator kriging and semi-variogram analyses were conducted using GSLIB (Geostatistical Software Library, Deutsch and Journel 1992) and WLSFIT (Heuvelink, 1993) was used for semi-variogram fitting.

Table 3.6: *Variogram analyses, using the spherical model, of the simulated tuber dry matter production for the different fertiliser doses.*

Application kg N ha^{-1}	*SS_D/SS_T*	*nugget $(t\ ha^{-1})^2$*	*Structure $(t\ ha^{-1})^2$*	*Range m*
250	0.191	0.186	1.071	46.54
200	0.191	0.186	1.071	46.54
175	0.188	0.185	1.065	46.65
150	0.188	0.159	0.862	47.37
125	0.175	0.111	0.633	48.49
100	0.145	0.064	0.406	52.32
50	0.155	0.022	0.128	56.74

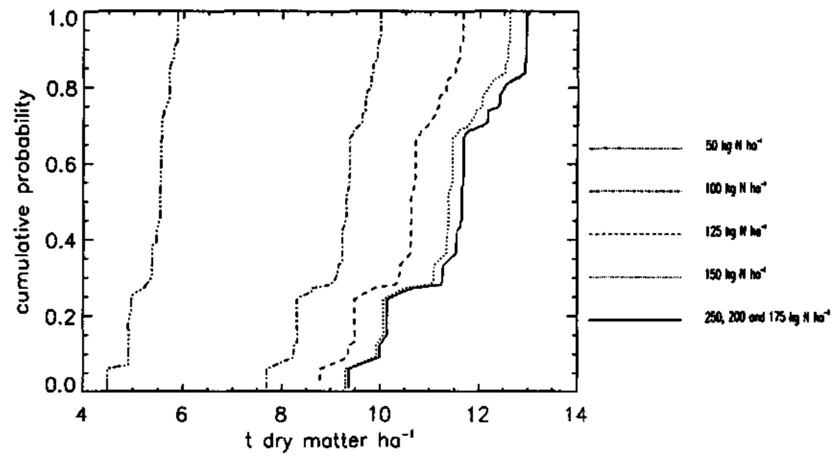

Figure 3.9: *Cumulative distribution functions of end yield for the different scenarios.*

Results

Model evaluation

The model was tested against measured data for the 1994 growing season. Figure 3.8 presents a comparison between simulation results and measured field data. The schematisation of the soil profile is reflected in the results of the calibration of the water content. The scatter in the end yield and mineral nitrogen is partly caused by variations in initial N and N application which could not be taken into account. The simulations appeared to be reasonably successful, allowing exploratory use of the simulation model.

Scenario evaluation

yield

Figure 3.9 shows the cumulative distribution functions of the yields. The functions reveal the highest production levels for the 250, 200 and 175 kg N ha^{-1} scenarios for these production levels are limited by water availability. Reducing the fertiliser rate to 150 kg N ha^{-1} mainly affects the high-producing clay and loamy parts of the field; indicating that nitrogen, and not water, becomes the growth limiting factor. With further reduction of fertiliser doses the yields drop dramatically. The recommended fertiliser application satisfies its goal of achieving the maximum production, but is 75 kg N ha^{-1}, too high for the year 1994 because nitrate leaching is unacceptably high.

Spatial yield patterns are obtained using ordinary kriging. Table 3.6 presents the results of the variogram analyses. The goodness of fit of the variogram is determined by the ratio SS_D/SS_T. Perfect fit is obtained when this ratio is zero, on a scale from zero to one. The values in Table 3.6 indicate a good fit. As expected, the variogram parameters for the first three fertiliser doses are identical.

Spatial variation (structure) decreases with decreasing fertiliser rate. The reverse can be observed for the range which increases to 56.74 meters. This results in a more uniform pattern as can be seen in Figure 3.10. From the spatially interpolated patterns (Figure 3.10) two main production units can be distinguished: (i) the relatively high productive part, loamy and clay parts and (ii) the relatively low productive sandy parts.

Leaching probability

From the cumulative probability functions for leaching (Figure 3.11 A+B) it is clear that for the recommended fertiliser dose nitrate leaching concentrations exceed the pre-set value of 50 mg nitrate dm^{-3} for all points. Reducing the dose with 50 kg N ha^{-1} has only a minor effect. Further reduction of the fertiliser dose to 175 kg N ha^{-1} reveals a dramatic improvement. A fertiliser dose of 150 kg N ha^{-1} shows a considerable change for the more loamy profiles in which the 175 kg N ha^{-1} dose shows high leaching probabilities. Reducing the rate with 25 kg N ha^{-1} reveals some improvement for the sandy parts. However, further lower fertiliser doses does not show much improvement; a fertiliser application of 50 kg N ha^{-1} shows a slight worsening of the probability of exceeding the pre-set threshold.

Table 3.7 presents the results of the variogram analyses. No results are given for the 250 kg N dose because the probability of exceeding the pre-set cut-off

Table 3.7: *Indicator variograms, spherical model, for the individual fertiliser applications.*

Application kg N ha^{-1}	SS_D/SS_T	*nugget* $(t\ ha^{-1})^2$	*Structure* $(t\ ha^{-1})^2$	*Range* m
250	-	-	-	-
200	*0.069*	*0.02*	*0.318*	*375.75*
175	*0.056*	*0.11*	*0.393*	*375.75*
150	*0.145*	*0.10*	*0.106*	*97.22*
125	*0.344*	*0.05*	*0.143*	*66.10*
100	*0.344*	*0.05*	*0.143*	*66.10*
50	*0.223*	*0.06*	*0.137*	*71.89*

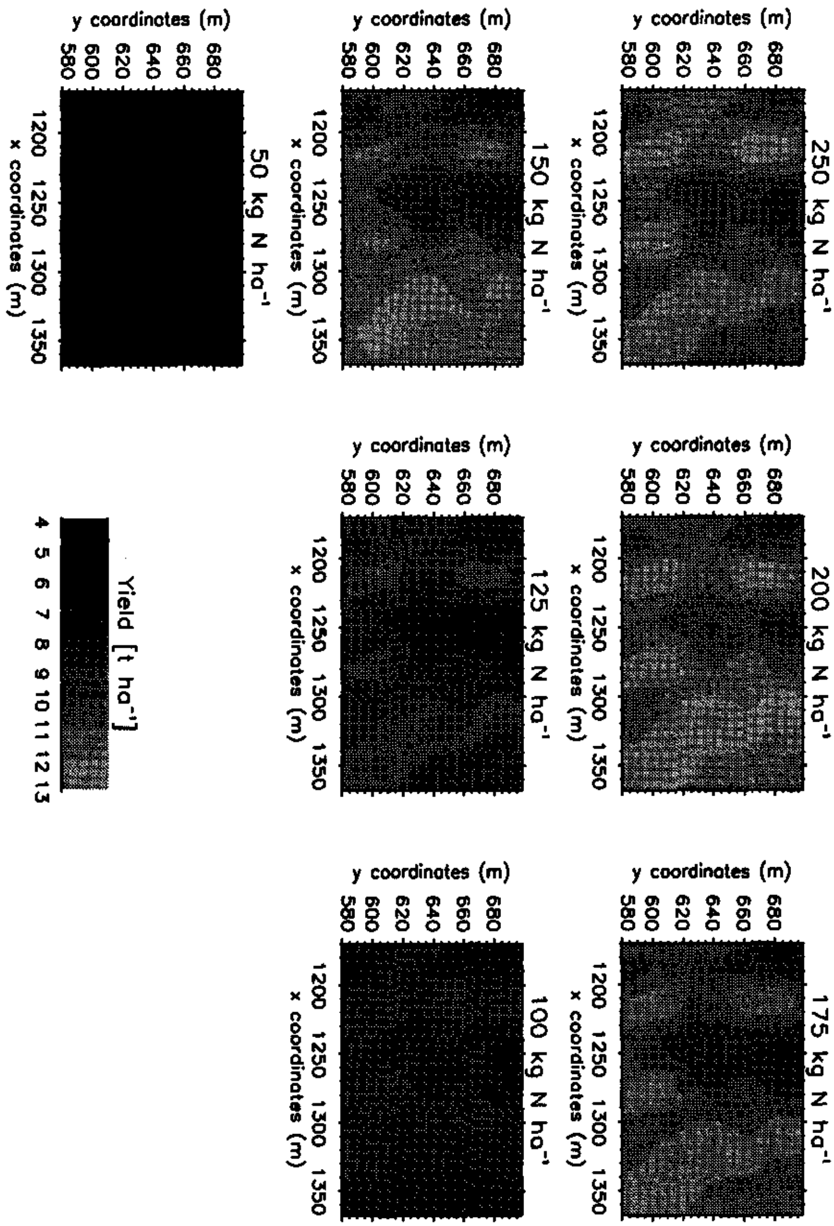

Figure 3.10: *Interpolated tuber yield maps [t dry matter ha-1] for the different fertilizer scenarios.*

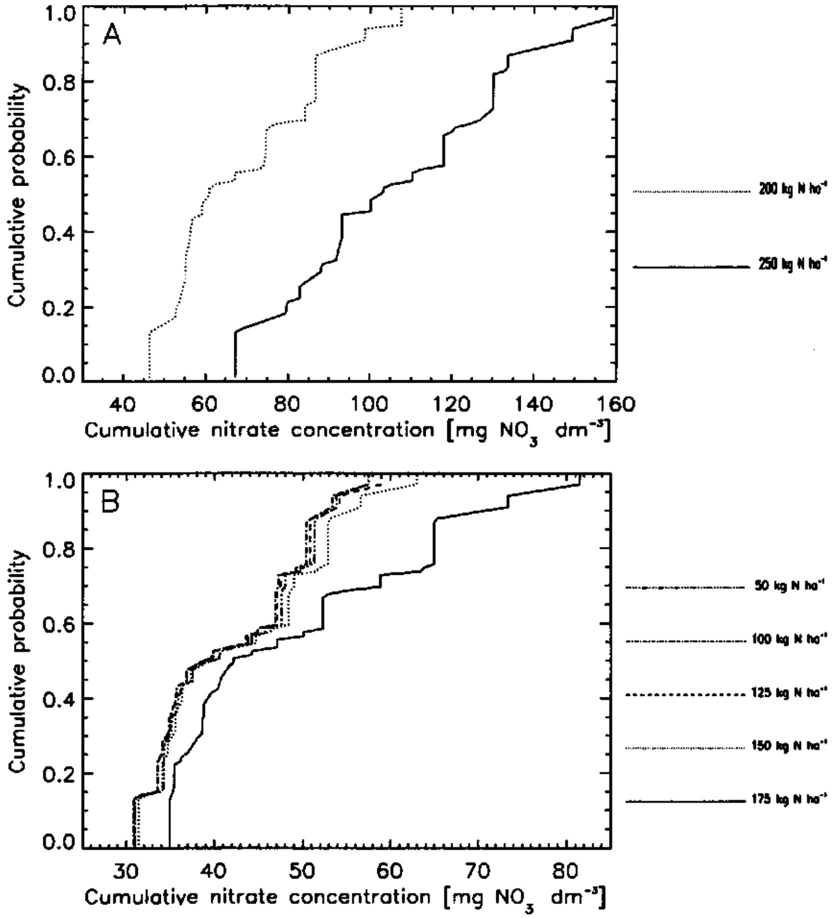

Figure 3.11: ***Cumulative distribution functions of the cumulative nitrate concentration for the seven scenarios.***

value is 100% for the entire field. Although there was a decrease in the spatial variability of tuber yield with increasing fertiliser level we see an increase in leaching probability. The spatial patterns of nitrogen leaching are expressed as the probability of exceeding the preset threshold value of 50 mg nitrate dm^{-3} and are shown in Figure 3.12.

Further decrease of the amount of fertiliser increases the leaching probability for the sandy parts but decrease for the loamy parts. The increase for the sandy parts can be explained by the low production levels and consequent low N uptake in combination with high hydraulic conductivity. An extreme low fertiliser application of 50 kg N ha^{-1} is associated with a slight increase in leaching probability.

Synthesis

Clearly, uniform fertiliser application on this farm field does not have a uniform effect on yield and nitrate leaching for the year 1994. For all scenarios, leaching probabilities for the sandy part are above the threshold value. Accepting a certain risk of pollution of the groundwater is the starting point to produce a site-specific fertiliser map. Figure 3.13 presents the relationships among fertiliser application, yield and leaching. High production levels and high nitrate losses are associated with high fertiliser rates. Small fertiliser doses result in low production levels and consequent small nitrate uptake so nitrate leaching does not decrease as might intuitively be expected.

A site-specific fertiliser application based on a less than 20 % chance of exceeding the pre-set threshold value of 50 mg nitrate dm^{-3} would imply excluding the sandy parts from production. The clay parts would receive a fertiliser dose of 175 kg N ha^{-1} and the intermediate parts would receive a dose of 150 kg N ha^{-1}. Accepting larger risks for the sandy parts and taking production levels into account, presents more realistic site-specific fertiliser recommendations (Figure 3.14). This scenario, based on weather conditions of 1994, will be referred to as the S-scenario.

Yield patterns will differ strongly among years, as was demonstrated by Van

Table 3.8: *Variogram analyses, using the spherical model, of the simulated tuber dry matter production for the two site specific fertiliser scenarios.*

Application kg N ha^{-1}	*SS_D/SS_T*	*nugget $(t\ ha^{-1})^2$*	*Structure $(t\ ha^{-1})^2$*	*Range m*
S-Scenario	*0.200*	*0.098*	*0.113*	*99.53*
B-Scenario	*0.258*	*0.081*	*0.145*	*82.19*

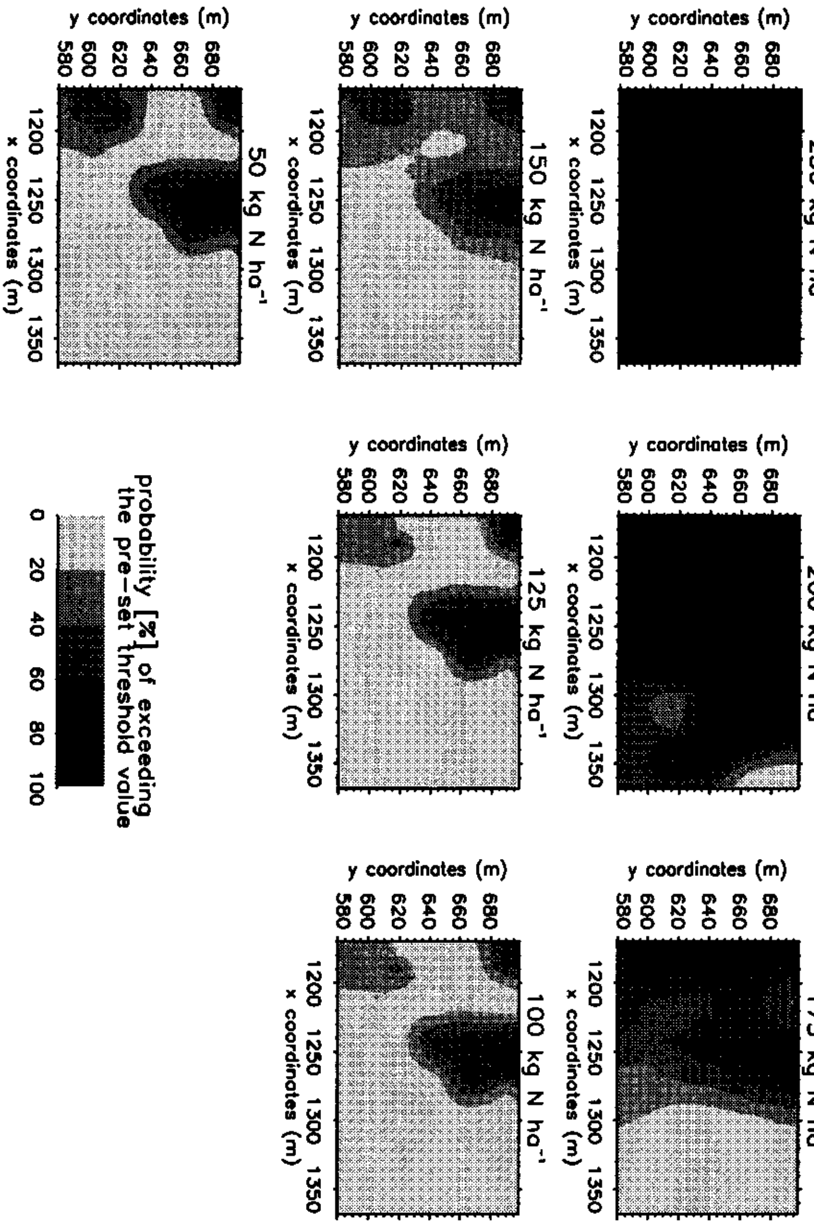

Figure 3.12: *Probability maps for the seven fertilizer doses of nitrate leaching exceeding a leaching of 50 mg* NO_3 *dm*$^{-3}$.

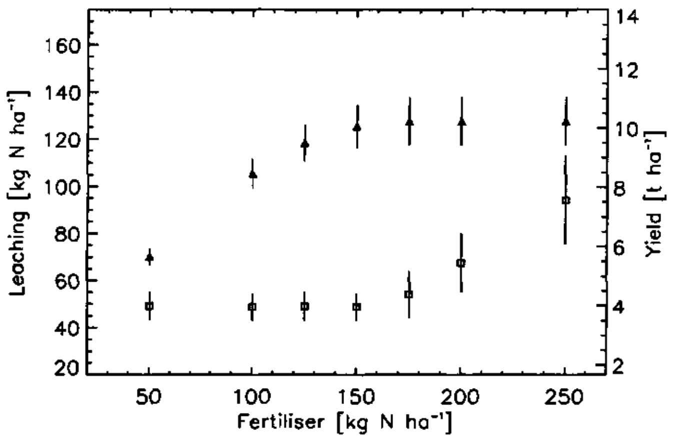

Figure 3.13: *Effect of fertiliser application on yield and leaching quantities for the individual scenarios.* $\triangle$ *yields [t ha^{-1}],* $\square$ *leaching quantities [kg N ha^{-1} yr^{-}1].*

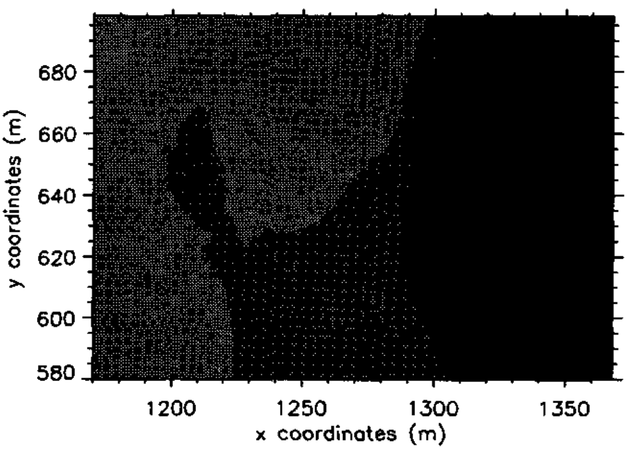

Figure 3.14: *Site specific fertiliser recommendation based on optimising production levels and minimising leaching probability for 1994. Unit I 125 kg N ha^{-1}, unit II 150 kg N ha^{-1} and unit III 175 kg N ha^{-1}.*

Table 3.9: *Indicator variograms, spherical model, for the two site specific fertiliser scenarios.*

Application kg N ha^{-1}	*SS_D/SS_T*	*nugget $(t\ ha^{-1})^2$*	*Structure $(t\ ha^{-1})^2$*	*Range m*
S-Scenario	*0.219*	*0.148*	*1.144*	*46.97*
B-Scenario	*0.112*	*0.037*	*1.800*	*48.65*

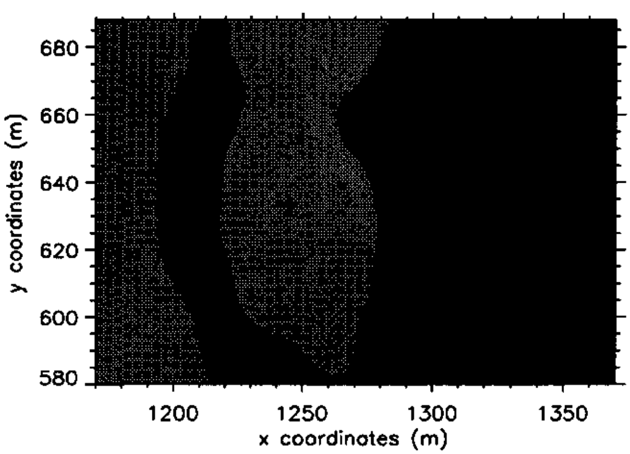

Figure 3.15: *Site specific fertiliser recommendation based on prototype pattern. Two management untis are distinguished: I. the sandy area receiving 125 kg N ha^{-1} and II the clay area receiving 175 kg N ha^{-1}.*

Uffelen et al. (1997), who by calculating water limited potato yields over a period of eight years, derived a dominant pattern for the study area, which expresses temporal variation among the years. This dominant or prototype pattern was proposed to be the standard pattern for site-specific management. Figure 3.15 shows a site-specific fertiliser map based on this standard pattern, aiming at maximising yields and minimising leaching risk. This scenario will be referred to as the B-scenario.

Figure 3.16 presents the results of the spatial interpolations and distribution functions of the two site-specific scenarios. Tables 3.8 and 3.9 show the variogram parameters. Yield patterns are quite similar and compare well with the yield levels for the 175 kg N ha^{-1} scenario (see Figure 3.10). The difference in yield between the scenarios is low as can be seen from the cumulative distribution functions. Spatial patterns of exceeding the critical nitrate concentration of 50 mg NO_3 dm^{-3} indicate for both scenarios high risk for the sandy area. Table 3.10 shows that both

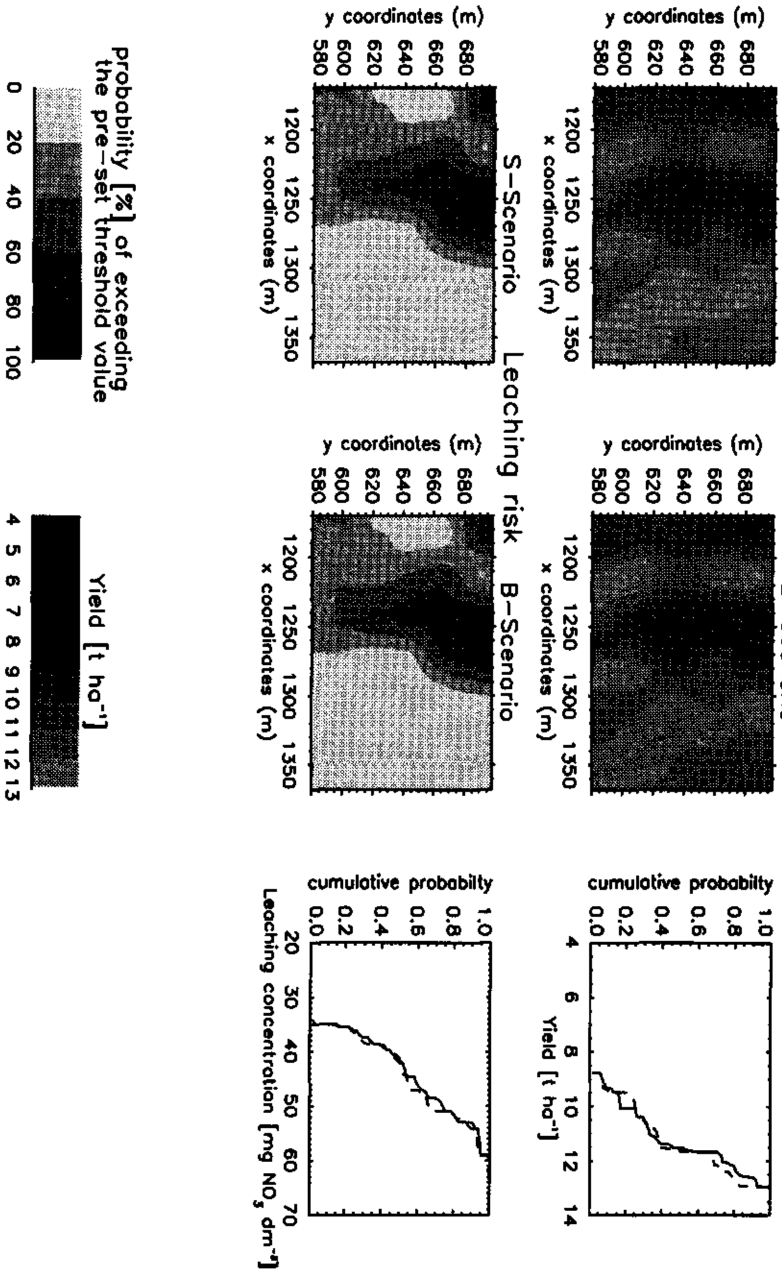

Figure 3.16: *Comparison of two site specific fertiliser applications. Solid lines mark the S-scenario, dashed line mark the B-scenario.*

Table 3.10: *Comparison of recommended and site specific fertiliser scenarios.*

Scenario	*Area*	*Rate* [kg N ha^{-1}]	*Average Yield* [t ha^{-1}]	*sd*	*Average NO_3 leaching* [kg NO_3 ha^{-1}]	*sd*
R-Scenario	*field*	*250*	*11.57*	*1.10*	*95.9*	*24.1*
B-Scenario	*I*	*125*	*9.78*	*0.76*	*47.3*	*5.7*
	II	*175*	*12.17*	*0.64*	*36.4*	*6.0*
	field		*11.29*	*1.34*	*39.7*	*7.0*
S-Scenario	*I*	*125*	*9.65*	*0.83*	*46.1*	*6.4*
	II	*150*	*11.47*	*0.98*	*40.9*	*5.0*
	III	*175*	*12.06*	*0.56*	*33.8*	*3.5*
	field		*11.13*	*1.21*	*39.3*	*6.9*

site-specific fertiliser scenarios display a dramatic improvement in leaching risk as compared to the recommended fertiliser scenario.

Conclusions

1. Recommended fertiliser application for potato was too high for the 1994 growing season and results in unacceptably high leaching risks.
2. Local differences in yield and leaching occur within the experimental field.
3. Adjusting fertiliser rates to local differences reduces the leaching risk and does not significantly reduce production levels.

Acknowledgments

This study is part of the AIR3-CT94-0480 project. The author thanks the farm manager H. Oosterhuis and P. Peters and E. Veldhorst for technical assistance. Thanks are also expressed to J. Bouma for critically reading the manuscript.

3.3 The role of post harvest soil N conditions for N leaching during the wet season [5].

Abstract

Nitrogen (N) in the Netherlands leaching mainly takes place during period September 15 - April 15 which is the period with a precipitation surplus. Soil mineral N after harvest is consequently the major source of nitrate pollution of groundwater. To reduce loss of nitrate to groundwater a national leaching threshold value of 35 kg N ha^{-1} $year^{-1}$ is defined based on the maximum nitrate concentration in the groundwater of 50 mg l^{-1} and the average annual precipitation surplus of 300 mm. Based on local weather conditions in the study area in the Northern part of the country, the leaching limit should be set at 42 kg N ha^{-1} $year^{-1}$. In this paper N profiles after harvest are defined which do not result in leaching quantities exceeding the national and local leaching thresholds. The spatial and temporal variability of N leaching is quantified using dynamic simulation for 65 soil profiles in a farmers field. Leaching is simulated for 5 different N profiles at the end of the growing season for a 20 yr period. For the given initial N range (15 – 120 kg N ha^{-1} m^{-1}) space-time relations for the wet period are linear. Different results among the 65 profiles soil types in both space and time are shown. The required N profile at September 15 is calculated for the national and local threshold values of 35 and 42 kg N ha^{-1} $year^{-1}$ respectively, using three risk levels of exceeding these thresholds. Spatial interpolation of the required N profiles results in N target maps which can be used to focus and evaluate N fertiliser management.

[5] *in press: Geoderma.* Verhagen, J. and Bouma, J. Defining threshold values for residual soil N levels

Introduction

The condition of Dutch soil and ground water resources has become an important environmental issue in recent years. The concern about soil and groundwater quality has led to government regulation to reduce pollutant losses. According to the National Environmental Policy Plan for the Netherlands (VROM, 1989) the nitrate concentration in the groundwater may not exceed 50 mg l^{-1} in the year 2000. With an average annual precipitation surplus of 300 mm in the Netherlands this means that only 35 kg N ha^{-1} yr^{-1} is allowed to leach. To achieve this goal, farm management has to reevaluate the use of N fertilisers. Implications of this policy are studied using multi-annual runs of a validated dynamic simulation model.

In the Netherlands, N leaching occurs mainly in the winter season ranging from 15 September to 15 April. Risk analyses, including aspects of spatial and temporal variability should therefore focus on this period.

Soil mineral nitrogen after harvest is the major source for nitrogen pollution of the groundwater (Corré, 1994; Van der Ploeg et al., 1995; Booltink and Verhagen, 1997). Farm management should aim at an N profile in autumn which has a low risk of exceeding a preset leaching limit during the wet season. This limit is usually based on a nitrate concentration calculated for the average precipitation surplus over a number of years, which is 300 mm for the Netherlands. Temporal variation of the leaching limit among the years does exist and is determined by the variation in precipitation surplus. The average value is used for regulatory purposes.

Booltink et al. (1997) showed that simulation models in combination with weather generators can be used to focus fertilisation practices in the growing season on a given N profile at the end of the growing season. This study tries to define these N profiles given the preset maximum threshold value of 50 mg nitrate per liter in the groundwater.

Materials and Methods

The study area is a 2.2 ha field on an experimental farm in the Wieringermeer polder in the northwestern part of the Netherlands. In the former mudflat both horizontal and vertical soil–spatial variability are high. The soils are strongly layered with textures ranging from sand to silty clay. Soils were classified as Typic Udifluvents silty, mixed, mesic. The potato crop (Saturna) of the 1994 growing season was harvested early September 1994. Winter wheat (Ritmo) and grass (Fuego) were sown on 25 October 1994. The short fallow between the 1994 harvest and the sowing of the winter wheat did not allow for the use of a catch crop. For further details reference is made to Finke and Bosma (1993) and

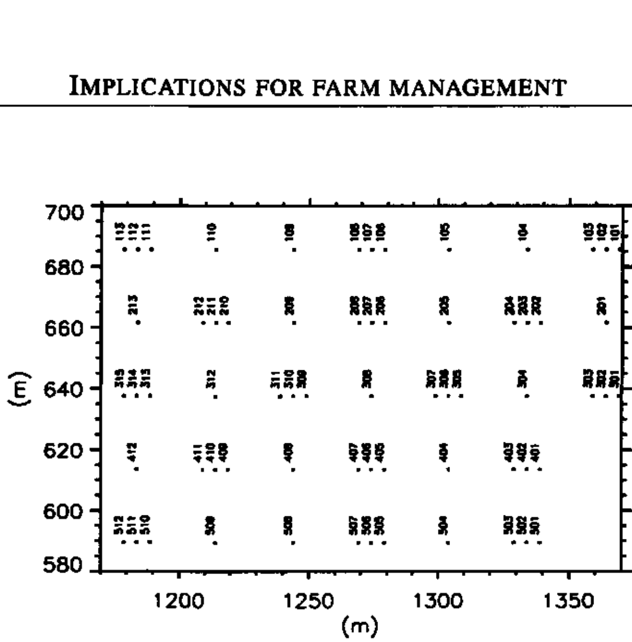

Figure 3.17: *Layout of the soil survey for the experimental field. Numbers refers to soil augerings.*

Verhagen et al. (1995a).

Soil physical characteristics

Soil augerings were made on a regular spatial grid with 65 observations including short distance observations to allow geostatistical analyses, (Figure 3.17).

The soils in the study area were characterised using four functional layers. Functional layers are layers that show identical hydrologic behaviour. To identify the functional layers a number of soil physical measurements were made. The crust method (Booltink et al., 1991) was used to measure the hydraulic conductivity at and near saturation. The retention and hydraulic conductivity curves at lower pressure heads were derived using the multi-step outflow method (Van Dam et al., 1994). Average retention and hydraulic conductivity curves were obtained for each functional layer by geometrically averaging five measured curves. The soils in the area were described using the four functional layers. Each of the 65 augerings were described as a sequence of functional layers with varying thickness. The hydrologic characteristics of the functional layers were used as input for the dynamic simulation model WAVE (Vanclooster et al., 1994; Verhagen et al., 1995a). Soil moisture was monitored using Time Domain Reflectometry (TDR) equipment biweekly during the growing season at 30 locations.

Soil nitrogen

The first soil mineral nitrogen sampling took place on 15 October 1994, ten days before sowing of the winter wheat. Three depths (0-30 cm, 30-60 cm , 60-90 cm) were sampled to establish a nitrogen profile for 44 locations for the study area. This first N sampling was used to initialise the simulation model.

An N sampling in early spring (13 February 1995) was done at two depths (0-30 cm, 30-100 cm) at 67 locations to define the N fertiliser demand. Total depth is based on the assumed rooting depth of 100 cm as defined in the national fertiliser recommendation guide (IKC, 1993). These data were used to validate the model. A third N sampling, at 67 locations, was done on 1 May 1995 just before the first fertiliser application using a regular grid with additional short distance observations.

Weather and groundwater

Daily precipitation and temperature data were recorded at the edge of the field. Global radiation data was obtained from a nearby (25 km) climatic station. Groundwater tubes were installed on 15 locations and groundwater depth was measured biweekly. Average groundwater depth was used as model input.

The average precipitation surplus for the data set of the study area is 358 mm. Based on this precipitation surplus the amount of N allowed to leach is to 42 kg N yr^{-1}. However, when taking the average precipitation surplus temporal variation of N leaching is ignored. The amounts allowed to leach during a dry year can be considerably less than the allowed leaching quantity during a wet year. Because of the unreliability of weather predictions, long term average values are commonly used accepting the fact that the leaching limit is exceeded during some years. In this study we focus on the space-time relations given a certain threshold value for N leaching.

Simulations

The choice of a process-based deterministic simulation model is crucial when extending the use of the model beyond the validation period. A major assumption is that the mechanisms of the processes do not change over time and once a soil-crop ecosystem is defined the same parameter set holds for other weather conditions than the ones used for calibration and validation.

Simulation of the soil-crop system was realised by using the dynamic simulation model WAVE (Water and Agrochemicals in Soil and Vadose Environment, Vanclooster et al. 1994). WAVE integrates four existing models, including dynamic simulation of water flow based on the SWATRER model (Dierckx et al., 1986), a

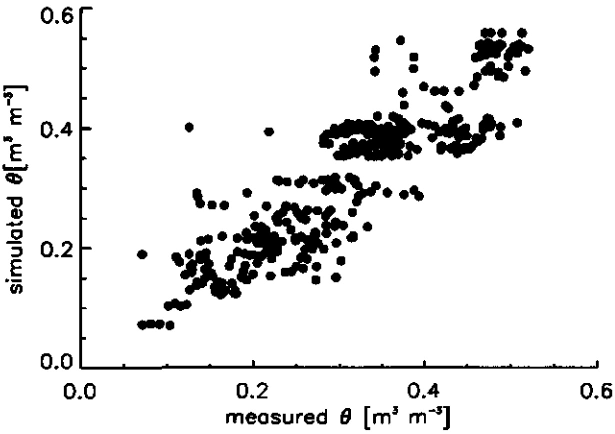

Figure 3.18: *Evaluation of the* WAVE *model by comparing measured and simulated water contents for the period September 1994 till August 1995.*

nitrogen model based on the SOILN-model (Bergström et al., 1991), a heat and solute transport model based on the LEACHN-model (Hutson and Wagenet, 1992) and the SUCROS crop growth model (Spitters et al., 1988).

Scenarios

The model is used to calculate expected nitrate losses during the wet season, ranging from 15 September to 15 April. Leaching risk is assessed for five different initial N profiles namely: 15, 30, 60, 90 and 120 kg N ha^{-1}, while N distributions in the soil profiles are based on the October 1994 measurements. Temporal variation was expressed by calculating leaching for 20 wet season. Periods are identified by the second year so the period from 15 September 1974 to 15 April 1975 is identified as the year 1975. The database created contains information on nitrate leaching for 5 different N-initial scenarios for 65 points for 20 periods.

Results and discussion

The model is evaluated on simulated water content and simulated N content. Monitoring of soil water content took place from 11 November 1994 to 20 July 1995. Simulated versus measured water contents (R^2 = 75 %) are presented in figure 3.18 . Data were collected at 30 monitoring locations at various depths. Measured and calculated N values agreed well as is illustrated for six locations (Figure 3.19).

Starting with high initial N levels amounts drop dramatically, each profile having its own trajectory but all reveal the large decrease in N.

Leached N quantities as a function of N present at September 15 are presented in figure 3.20 for 6 selected years for all 65 locations. Each line represents the behaviour of an individual soil profile: within field spatial variation is consequently defined by the bandwidth. Low leaching quantities are associated with relative low precipitation surpluses. The 42 kg N ha^{-1} limit, based on the average precipitation surplus of the area, is shown in figure 3.20 to illustrate the allowable spatial range of N contents for the entire field for each year.

A selection of 6 soils, from the 65 locations, were used to illustrate the variation in leaching behaviour for the 20 seasons. Figure 3.21 presents the relationship of initial N profile and the subsequent nitrate leaching. Relative low leaching amounts but large temporal variation is observed for the clayey profile (201) while the behaviour of the sandy profile (311) is more stable in time and the leaching quantities are much higher. The remaining 4 profiles are intermediate forms of the two extremes. Variation in time, indicated by the spread of the lines, is higher for the clayey profiles but leaching quantities are lower as compared to the sandy profiles.

Risk

Risk reflects both variation in space and time (figures 3.20 and 3.21, respectively), and is here defined as the probability that the critical nitrate concentration, 50 mg l^{-1} is exceeded during the wet season. The threshold value to evaluate the risk is defined by the amount of nitrate allowed to leach during the wet season.

For each location risk is expressed using cumulative distribution functions. Figure 3.22 displays the probability at any locations (based on 20 years of data) that nitrate is leached for the 5 initial N scenarios, as defined earlier in the methods section. No risk, when leaching never exceeds the threshold value, is indicated by the 1.0 level while at the 0.0 level the threshold values is exceeded for all periods. Allowing 10 % of the periods to exceed the threshold value the 0.9 probability level is read. Example: a threshold value of 50 kg nitrate. For profile 105 the scenarios with 15 and 30 kg N ha^{-1} m^{-1} result in nitrate leaching which for all periods is below the threshold value. The 60 kg N ha^{-1} m^{-1} intersects with the threshold value at 0.5 indicating exceedance for 50 % of the periods. Both the 90 and 120 kg N ha^{-1} m^{-1} scenarios always result in leaching quantities above the threshold value. For profile 201 the threshold value is exceeded for 90 % of the periods for the 90 kg N ha^{-1} m^{-1} scenario. The scenarios of 15, 30 and 60 kg N ha-1 m-1 do not exceed the set threshold of 50 kg nitrate while the 120 kg N ha^{-1} m^{-1} scenario does exceed the threshold for all periods.

The risk levels have a larger impact on the clayey areas than on the sandy areas.

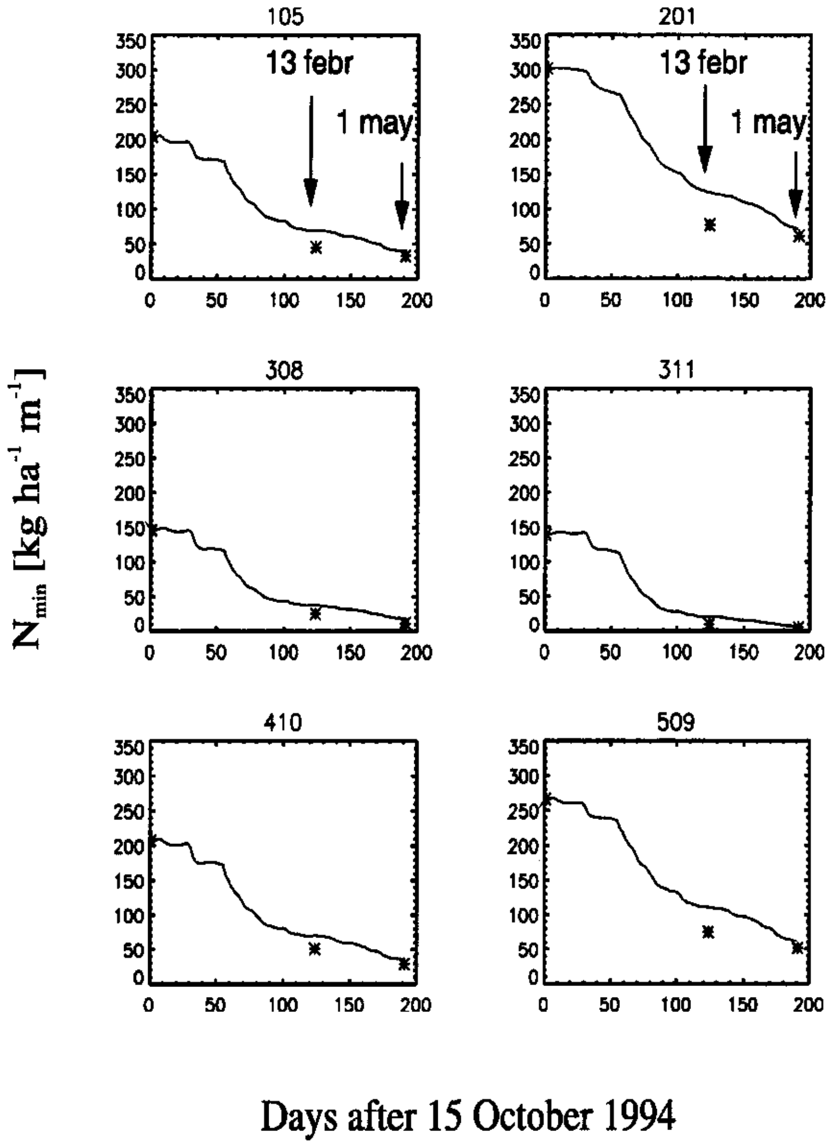

Figure 3.19: ***Evaluation of the* WAVE *model by comparing measured and simulated N profiles (0 - 100 cm.) in six representative soils.***

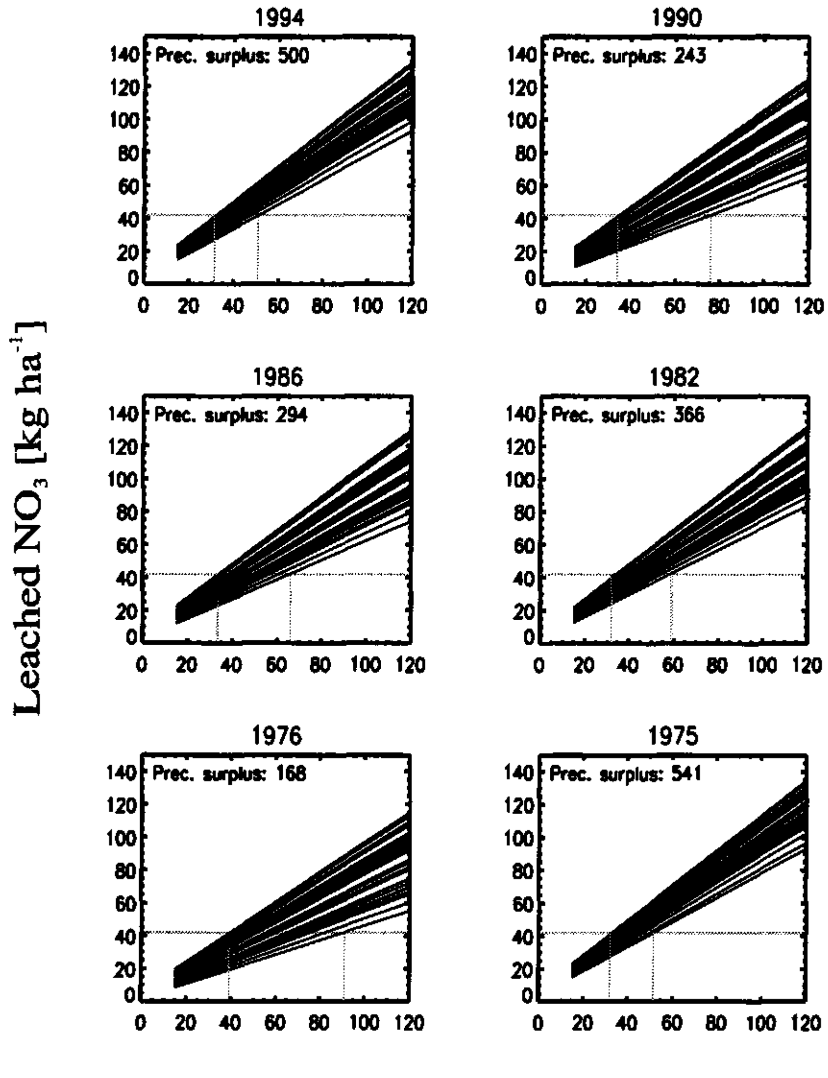

Figure 3.20: *Variation in space illustrated for six representative years. Each line displays the leaching behaviour of a soil profile for the indicated year given. The vertical gray lines indicate the range allowed of initial N, corresponding with leaching of 42 N kg* ha^{-1}.

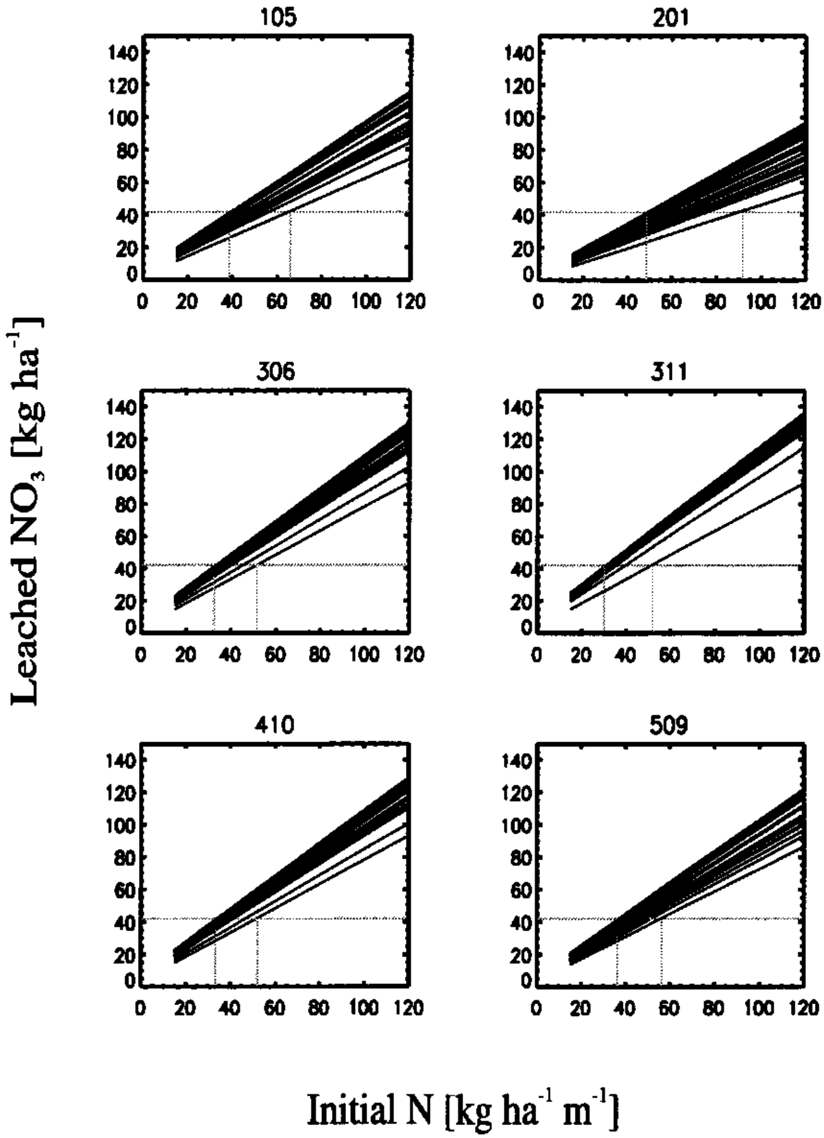

Figure 3.21: *Variation in time illustrated for six representative profiles. Each line represents the leaching behaviour of the indicated soil profile for a specific year. The gray vertical lines indicate the allowed range of initial N for a 20 year period, corresponding with a leaching of 42 N kg ha^{-1}.*

This can be explained using figure 3.22 were cumulative distribution functions for the sandy profile (311) are rather steep, revealing hardly any variation in time, as compared to the more sloping cumulative distribution functions for the clayey profile (201). The choice of the threshold value also has a larger impact on the clayey profile (201) as compared to the sandy profile (311) as indicated by the relative short distance between the individual cumulative distribution functions for the former.

The linear relationships found for time and space (figures 3.20 and 3.21) allow linear interpolation between the initial N scenarios in figure 3.22 when evaluating various combinations of risk levels and threshold values. Critical quantities of N within 100 cm of soil at September 15 will now be defined, assessing the three risk levels: 0 %, 10 % and 20 %.

The national policy plan allows leaching of 35 kg nitrate per year. Based on figure3.22 an assessment for the three risk levels for all 65 points is made using the 35 kg nitrate threshold value, allocating a specific N-profile to each individual point for each risk level. The same analysis is done for the local threshold value of 42 kg nitrate leaching per year. The result is a matrix containing information on 2 threshold values (35 and 42 kg nitrate) for three risk levels (0 %, 10 % and 20 %) for 65 locations.

Spatial patterns

The spatial pattern of the required 15 September N profile for each combination of threshold value and risk level based on the 65 points (figure 3.23). was created by ordinary kriging (Journel and Huijbergts, 1978)

For both threshold values and all three risk levels comparable patterns were observed: relatively low N concentrations are located on the left part of the field, corresponding with the sandy area, while higher N concentrations are found on the right part of the field, corresponding with the clayey area.

Depending on the defined threshold and accepted risk level the autumn N-profile can be set as a target for farm management. Reacting to local differences, fertiliser rates and frequency can be set to achieve the set target (Booltink et al., 1997).

Conclusions

1. Spatial and temporal differences in N behaviour in soils can be quantified using dynamic simulation models, as is specifically illustrated in this study.

2. The relation between the N profile on 15 September and nitrate leaching is linear over time and space for the initial N range of 15 - 120 kg N ha^{-1} m^{-1}

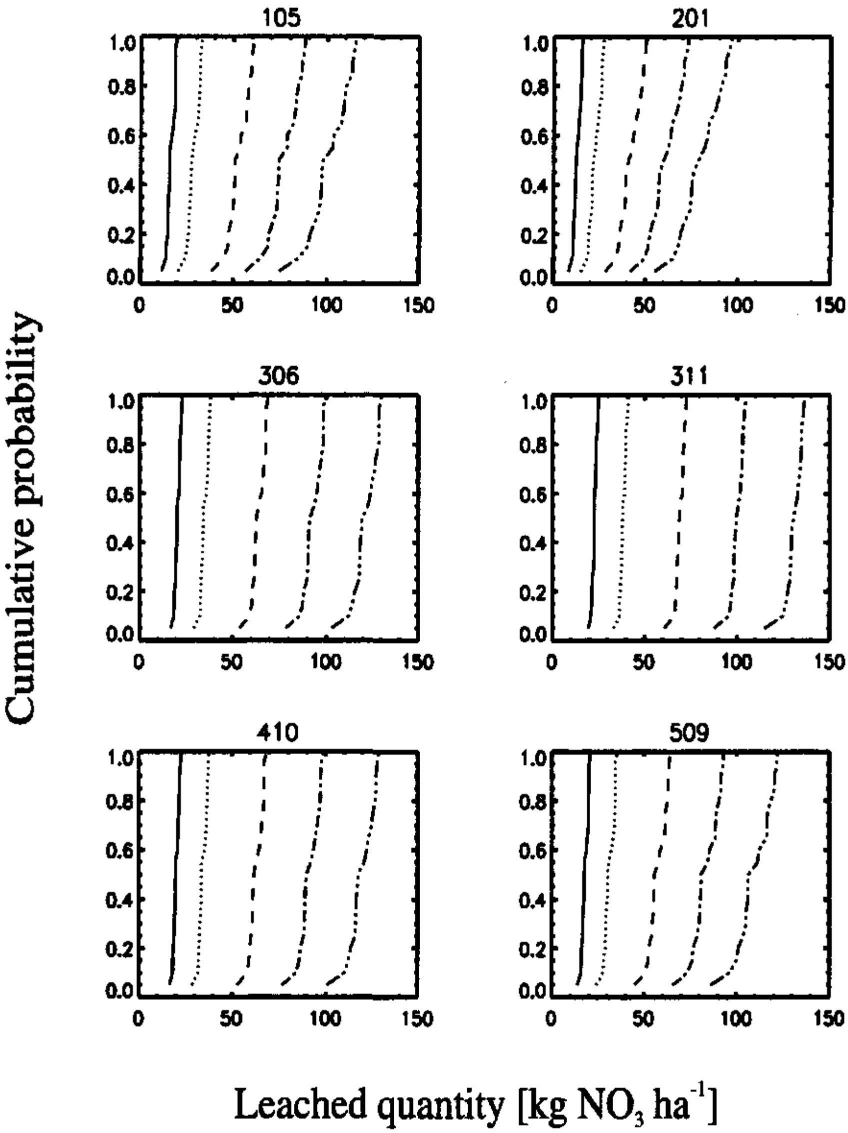

Figure 3.22: *Leaching probabilities (based on 20 years) given an initial N profile for six representative profiles. Initial N profiles at 15 September: ——— 15 kg N ha^{-1} m^{-1}, ········· 30 kg N ha^{-1} m^{-1}, – – – – – 60 kg N ha^{-1} m^{-1}, – · – · – · 90 kg N ha^{-1} m^{-1}, ···—··· 120 kg N ha^{-1} m^{-1}.*

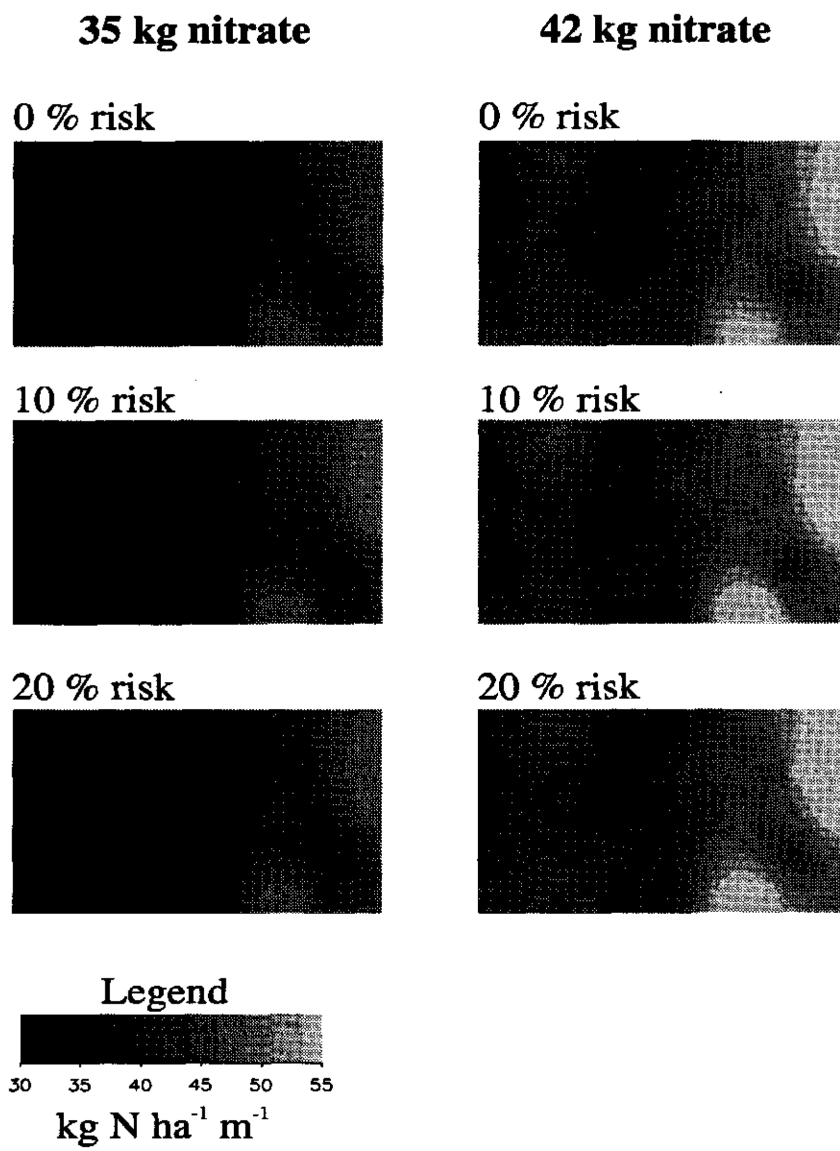

Figure 3.23: *Target maps of the N profile (kg ha^{-1} m^{-1}) at September 15 for two threshold leach values and three risk levels of exceeding these threshold of 35 kg N ha^{-1} and 42 kg N ha^{-1}.*

for all studied profiles. Hence the critical N profile at 15 September for a given soil can be quantified for each given threshold value (within the given N range) and acceptable risk level.

3. Threshold values for nitrate leaching should be based on local rather than generalised national weather conditions.

4. Target N maps with N profiles at 15 September are attractive to be used to focus farm management with the objective to reduce leaching risks below acceptable levels.

Chapter 4

Balancing production and environmental criteria in practice [6]

Abstract

For a farm field two soil patterns were distinguished for precision agriculture, considering the effects of multi-year weather variability. The first pattern (A) relates to crop production, during the "dry" season of April to September while the second pattern (B) relates to N leaching during the remaining "wet" season. Pattern A is to guide management practises during the growing season; pattern B resulted from an assesment of N leaching during the "wet" season considering legal threshold values. This study focuses on the question how pattern B affects management during the growing season.

Three representative profiles for the soil units are identified and tested for internal homogeneity, by considering temporal variability of nitrate leaching during the "wet" season.

Carry-over effects of N fertiliser management during the growing season to the "wet" season were quantified for the three representative profiles by simulations for an 11 year period. Thus, a probabilistic interpretation of five fertiliser scenarios resulted in recommended site specific N fertiliser applications that allow high levels of potato production without exceeding the legal threshold. The latter is expressed in terms of probability of exceedance.

---

[6]*submitted to: Agriculture, Ecosystems & Environment.* Verhagen, J. and Bouma, J. Focus N fertiliser practices during the dry season on post harvest soil N conditions.

Introduction

Until recently farm management in the Netherlands focused mainly on achieving high production levels. Consequently, management actions were mainly aimed at the growing season. Fertiliser applications were evaluated considering benefits for the crop only and post harvest soil conditions were mainly evaluated in terms of seed bed quality and trafficability for the coming growing season. Environmental awareness has led to a change in farm management. Modern farm management aims at optimising economic and environmental objectives. Environmental and economical threshold values define the boundary conditions under which the farm manager must operate. Site specific management provides a framework in which both objectives are not necessarily conflicting as is shown by (e.g. Booltink and Verhagen, 1997; Bouma, 1997a).

It is, however, difficult to focus farm management on long-term soil and crop conditions. The key factor here is the unpredictability of the weather; the main driving force for crop growth and nitrate leaching. Dynamic simulation models have proven to be useful tools in exploring the soil-crop ecosystem (Booltink et al., 1997; Sadler and Russell, 1997; Verhagen, 1997). and modelling is therefore a useful tool to focus management on long-term goals.

The three main questions for site specific fertiliser management are: "what" (e.g. how much N), "where" (location) and "when" (timing). This paper deals mainly with the first two questions: how much nitrogen fertiliser to apply in order to obtain economically acceptable yields in an environmentally acceptable manner. The trade-off between yield and environmental impact is still biased because pollution cannot as yet be quantified in economical terms (Bouma, 1997b).

This paper will discuss the effects of fertiliser applications on crop production and leaching during both the "dry" growing season (April - September) and the "wet" season (September - April). The leaching potential during the "wet" season is based on critical N contents at September 15 as described by Verhagen and Bouma (1997). The key aspect is the question as to how the critical N contents on September 15 can be translated into management measures for N during the growing season, thus linking the requirements dictated by the "wet" season with those for N management in the "dry" growing season.

For a farm field in the north of the Netherlands basic information on soils and crops was collected during a period of two years. Three representative soil profiles were selected for the three parts of the field that show significantly different behaviour over the years. For each profile, potato production, leaching and leaching potential were calculated for a period of 10 years allowing a probabilistic interpretation of the simulation results.

Materials and methods

Simulation model

Simulation of the soil-crop system was realised by using the dynamic simulation model WAVE (Vanclooster et al., 1994). WAVE integrates four existing models, including dynamic simulation of water flow based on the SWATRER model (Dierckx et al., 1986), a nitrogen model based on the SOILN-model (Bergstrm et al., 1991), a heat and solute transport model based on the LEACHN-model (Hutson and Wagenet, 1992) and the SUCROS crop growth model (Spitters et al., 1988).

The model is used to calculate potato production (spp. saturna). The calculations start on 20 May (day of emergence) and end at harvest on 10 September.

The total water uptake is calculated as the integral over the root zone. Water stress is calculated according to Feddes et al. (1978), in which the maximum water uptake is defined by a sink term as a function of depth. Water uptake is reduced at characteristic high and low pressure-head values. The optimal water uptake is defined between pressure head values of -50 cm H_2O and -1000 cm H_2O. For high the pressure head a value of -10 cm H_2O was taken and the wilting point was set at -8000 cm H_2O. Maximum rooting depth was set at 60 cm depth and was based on field observations.

Stress resulting from nitrogen deficiencies is calculated using the "critical nitrogen concentrations" as defined by Greenwood and coworkers (Greenwood et al., 1985, 1990). They describe the decrease in N percentage with increasing plant mass. The supply side is defined by the connective and diffusive uptake. When the actual uptake is insufficient to sustain the necessary N concentration in the plant, biomass production is proportionally reduced to the ratio of the actual and required uptake. Model performance was tested for this specific case by Verhagen et al. (1995b) and Verhagen (1997).

Spatial patterns

In earlier studies two patterns (figures 4.1 and 4.2) were identified for the field. Based on seven years of simulated water-limited production two management units were defined (Van Uffelen et al. 1997, Figure 4.1), this pattern will be referred to as pattern A. For the same field Verhagen and Bouma (1997) identified areas with different leaching potential. They defined a postharvest N map as a target for overall farm N management (pattern B, Figure 4.2). Both patterns A and B are soil-related. The patterns do not match perfectly, because crop growth is mainly affected by the top soil layers (rooting zone) while losses of nitrate to the groundwater are also governed by conditions in the lower soil layers.

The main difference between the two patterns can be found on the right part of the field. This area is identified by Van Uffelen et al. (1997) as the highly

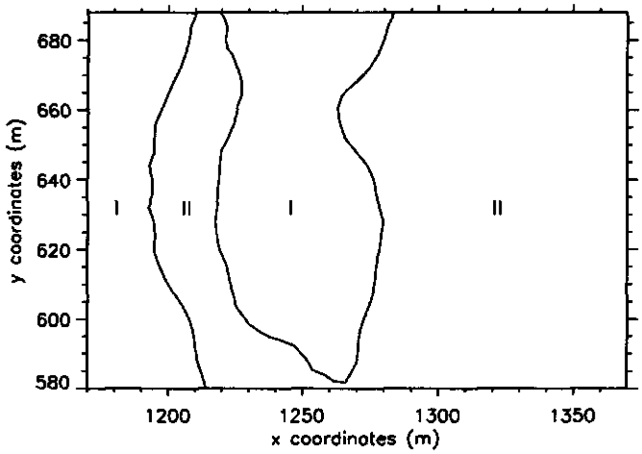

Figure 4.1: *Site Specific management units based on seven years simulated water limited production. (After Van Uffelen et al. 1997).*

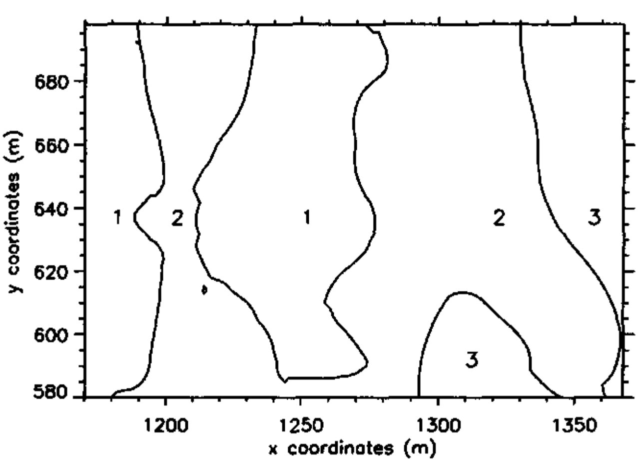

Figure 4.2: *Postharvest N map based on 20 years simulated leaching during the September 15 and April 15 period. (After Verhagen and Bouma 1997).*

productive area (II). The low productive areas, located at the centre and left (I), were identified as areas with more sandy soils with a relatively high leaching probability. Unit 3 on map B represents a lower leaching potential than unit 2, while production is not sufficiently different from unit II on map A to justify a third distinction on map A.

Because pattern B reveals the most detail and the two patterns (A and B) are complementary and not conflicting, representative soil profiles are selected based on pattern B.

Representative profile

The soils in the experimental farm "Prof. van Bemmelenhoeve" were all classified as Typic Udifluvents (Soil Survey Staff, 1975). Soil descriptions were made for 65 profiles in the experimental field using the functional layer concept. Functional layers consist of pedogenetic horizons that show similar physical behaviour (Verhagen et al., 1995b). Four functional layers were identified for the experimental field, see Table 4.1 (Verhagen et al., 1995b).

Verhagen and Bouma (1997) showed that leaching during the "wet" season is linearly related to the amount of nitrate in the soil profile at September 15. By running the model for 20 years the temporal variation was included in their analyses. They found that each soil profile has a distinct behaviour with respect to leaching.

Figure 4.3 displays a schematic representation of their results. All profiles can be characterised using:

i. The average angle indicating the average amount of nitrate leached during the "wet" season in relation to the amount N at September 15.

ii. The maximum angle which indicates the maximum amount of nitrate leached during the "wet" season in relation to the amount of N at September 15

Table 4.1: *Basic soil data for the four functional layers.*

Layer	*ρ [kg dm^{-3}]*	*(sd)*	*Org. matter %*	*Clay %*	*K_{sat} [cm day^{-1}]*	*θ_{sat} (sd)*	
F1	*1.48*	*(0.039)*	*0-2*	*0-4*	*183*	*0.40*	*(0.02)*
F2	*1.21*	*(0.079)*	*0-2*	*4-11*	*128*	*0.48*	*(0.04)*
F3	*1.08*	*(0.231)*	*0-2*	*11-23*	*36*	*0.59*	*(0.06)*
F4	*1.30*	*(0.045)*	*0-3*	*4-23*	*265*	*0.44*	*(0.08)*

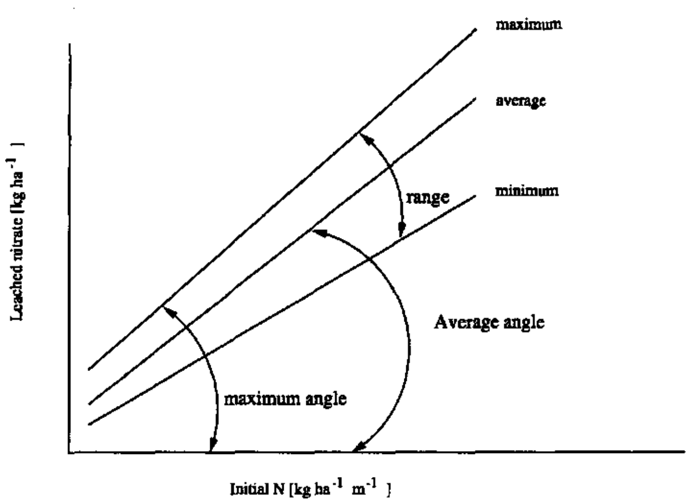

Figure 4.3: *Schematised relation of N (kg ha^{-1} m^{-1}) at 15 September and leached nitrated during the "wet" period (15 September - 15 April) for a soil. Average angle indicates the (20 years) average leaching rate. The range indicates the temporal variation in leaching rates.*

iii. The range which indicates the temporal variation of this relation.

All 65 soils were characterised using the average leaching rate, maximum leaching rate and the range. The soils were grouped based on the three units identified in pattern B resulting in an average value of the before-mentioned elements for each of the identified units. Thus a representative profile for each of the three the individual units was defined.

Scenarios

The three units were studied separately using the three representative profiles. An assessment of the effect of fertiliser level on three soil quality indicators was made: (1.) postharvest N, (2.) N leaching and (3.) potato production. For the three soils an initial N profile of 30 kg ha^{-1} 0.6 m^{-1} is defined. This initial N profile and N distribution over the profile is based on measured N profiles during two years of monitoring. The recommended fertiliser dose calculated according to national guidelines (IKC, 1993) is 250 kg ha^{-1}. In addition, also fertiliser doses of 150, 175, 200 and 225 kg N ha^{-1} were included in the scenario analyses. For the three profiles each scenario was calculated for 11 "dry" seasons (1984 - 1994).

Verhagen and Bouma (1997) defined critical post-harvest N concentrations for the experimental field that would result in acceptable leaching of nitrates. The selected threshold values are based on maximum leaching of 42 kg N during the "wet" season and are 40, 47 and 52 kg N ha^{-1} m^{-1} for unit 1, 2 and 3 respectively. Linking the management units and post-harvest N levels allows analyses of potential leaching after the growing season and definition of acceptable fertiliser-application levels for the three soil types from both an economical and environmental point of view. Note that only a single N application is considered, which is in agreement with the national recommendation. Temporal variation (or risk) is included considering results for the 11 "dry" growing seasons.

Results and Discussion

Representative profile

The soils of the three units of pattern B are grouped and tested in terms of the average, maximum and range of the relation between the amount of N at September 15 and the amount of nitrate leached during the "wet" season. From the results of the two-tailed multivariate ANOVA (Table 4.2) it is concluded that all three groups are significantly different for all three elements.

From table 4.2 it is also clear that the leaching risk is highest for unit 1 and lowest for unit 3. Temporal variability, as expressed by the range, is highest for units 2 and 3. Spatial variation expressed by the standard deviation of the average, is highest for unit 2.

The representative profiles are selected from the 65 available profiles based on similarity with the average values for each unit as described in table 4.2. Table 4.3 presents the average angle, maximum angle and range for the three representative profiles. The soils are numbered according to the units presented in figure 4.2. The representative soil profiles, described using the functional layer concept, are presented in table 4.4.

Scenarios

The fertiliser scenarios are evaluated based on three soil quality indicators:

Table 4.2: *Results of the two-tailed multivariate ANOVA (MANOVA, LSD) with replicates for the soil groups. *significant at the 0.01 level. Average, max. and range are explained in the text.*

unit	*Average angle*	*(sd)*	*Max. angle*	*(sd)*	*Range*	*(sd)*	*Number*
1	*33.72**	*(2.55)*	*38.94**	*(2.49)*	*18.38**	*(0.14)*	*14*
2	*40.25**	*(5.49)*	*44.07**	*(2.41)*	*15.51**	*(2.41)*	*26*
3	*44.32**	*(1.97)*	*45.92**	*(1.34)*	*11.32**	*(1.84)*	*25*

i. the postharvest N contents.

ii. the leached nitrate during the "dry" growing season.

iii. the production level.

The results of the scenario analyses expressed as 11 year averages including standard deviations are presented in Figure 5.

From Figure 4.4 A we can see that fertiliser doses above 200 kg N ha^{-1} have a dramatic impact on postharvest N. N uptake by the crop doesn't increase (see figure 4.4 C) so either the added N above 200 kg N ha^{-1} contributes to the postharvest N (figure 4.4 A) or to leaching during the "dry" growing season (Figure 4.4 B). Temporal variation (Figures 4.4 a, b and c) is highest for all three indicators for soil 1. Different climatological conditions have a larger impact on this soil as compared to the other two. Soils 2 and 3 are stable with respect to all the three indicators. The recommended fertiliser rate (250 kg N ha^{-1}) results in high production levels for all three soils but postharvest N values are unacceptably high.

Cumulative distribution functions for the three soil quality indicators are presented in Figs. 4.5, 4.6 and 4.7. Figure4.5 presents the postharvest N levels for the 5 fertiliser doses. As discussed, critical postharvest N levels are 40, 47 and 52 kg N ha^{-1} for soil 1, 2 and 3 respectively. Both soils 2 and 3 show comparable behaviour. Temporal variation of postharvest N for soil 3 is high, especially for the high fertiliser doses. For the 250 kg N ha^{-1} dose the limits are 40 and 105 kg N ha^{-1} m^{-1}, for soils 2 and 3 the limit ranges from 55 to 82. For soil 2 and 3 the low fertiliser doses (150, 175 and 200 kg ha^{-1}) are stable in time and result in low postharvest N ($<$ 40 kg N ha^{-1} m^{-1}).

Taking the threshold value (52 kg N ha^{-1} m^{-1}) for unit 3 we can read that about 15 % of the years is still within acceptable limits for the 225 kg N ha^{-1} dose. For soil 2 this is 20 % of the years for the 225 kg N ha^{-1} dose. Soil 1 displays a different behaviour. The 200 kg N ha^{-1} dose results for 85 % of the cases in an acceptable postharvest N while this value is 20 % for the 225 kg N ha^{-1} dose.

Table 4.3: *The average, max. and range for the selected representative profiles. Average, max. and range are explained in the text.*

unit	*average*	*max.*	*range*
1	*32.70*	*37.89*	*18.41*
2	*40.57*	*43.72*	*15.50*
3	*43.80*	*45.66*	*11.61*

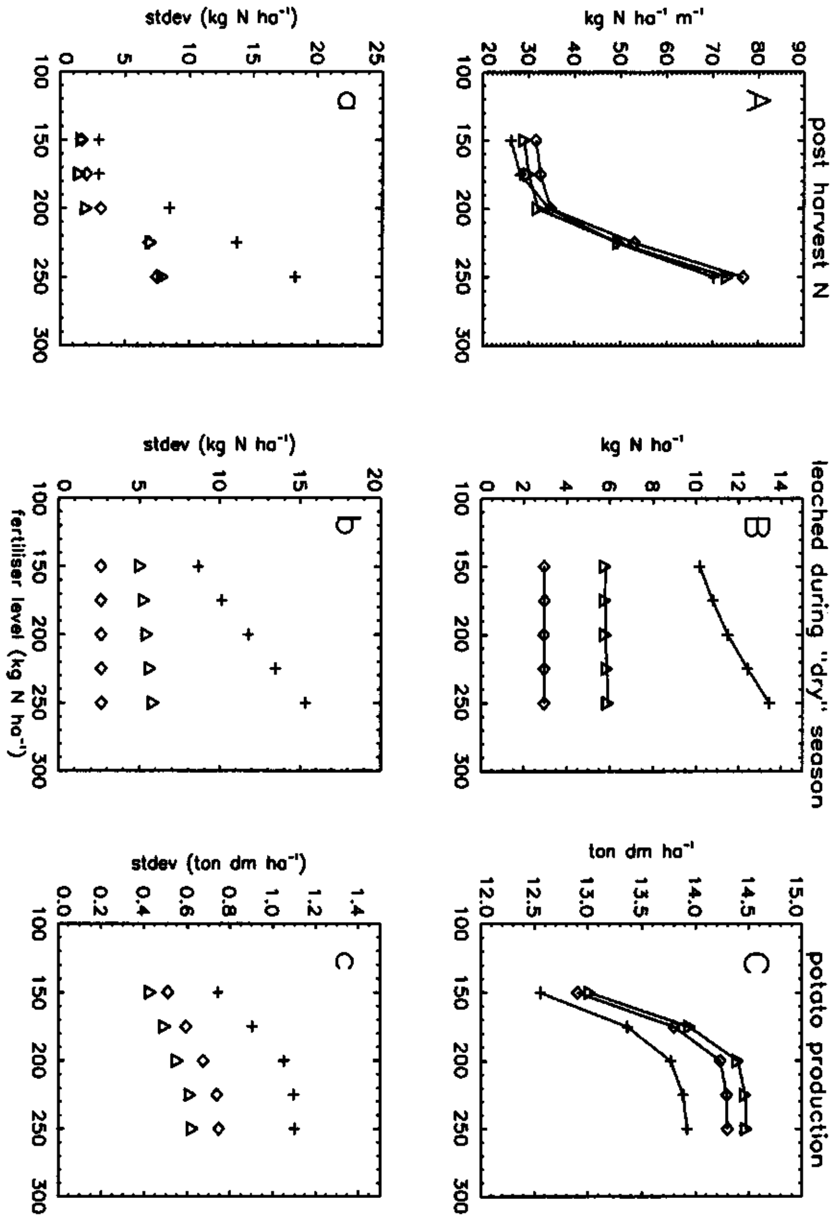

Figure 4.4: *Average (A, B, C) and standard deviation (a, b, c) of postharvest N, leached N during the "dry" season and potato production levels for the three soils. Average and standard deviation are based on 11 years of simulated data. + indicates soil 1, △ indicate soil 2 and ◇ indicates soil 3.*

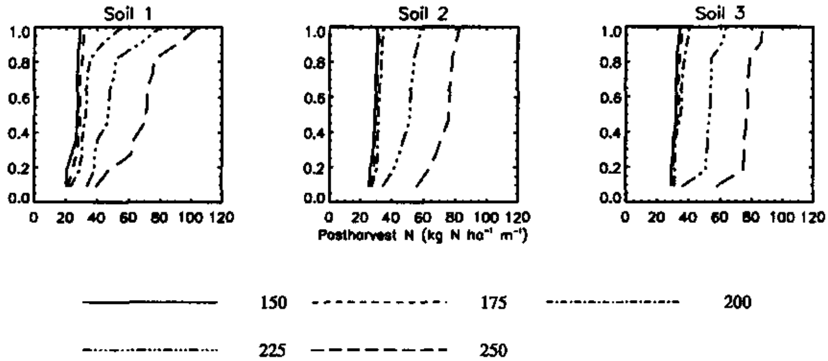

Figure 4.5: *Cumulative distribution functions of postharvest N for the different fertiliser doses [kg N ha^{-1}] for the three soils.*

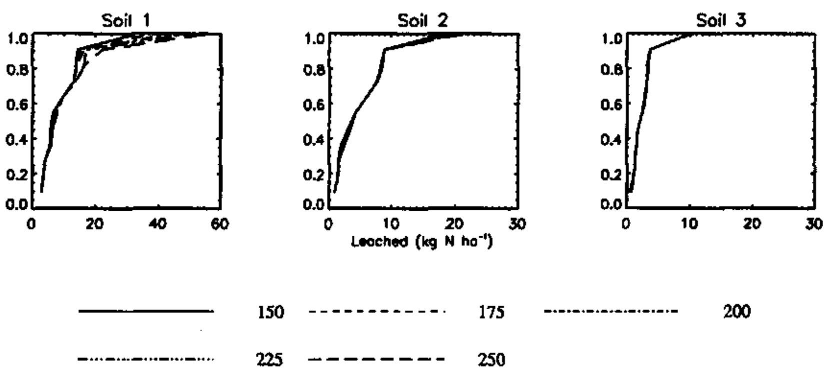

Figure 4.6: *Cumulative distribution functions of leached N during the "dry" season for the different fertiliser doses [kg N ha^{-1}] for the three soils.*

Table 4.4: *The three representative profiles, for the map of figure 4.2 Profile numbers refer to the unit numbers presented in figure 4.2. Profile characteristics refer to functional layers as described in table 4.1.*

Unit	*1*	*2*	*3*
Profile	F4 / F1 30 cm.	F4 / F3 30 cm. / F2 60 cm.	F4 / F3 30 cm.

Correcting for occasionally leached N during the "dry" season would mean readjusting the threshold values using figure 4.6. The correction would have the largest impact on soil 1. Taking the 50 % cut-off values, a correction of 10 kg N ha^{-1} should be made. Because leaching quantities during the "wet" season are linear with N contents on September 15, the correction is a simple subtraction. The corrected threshold for soil 3 now becomes 30 kg N ha^{-1} m^{-1}.

The implications of this correction are that the 225 kg N ha^{-1} fertiliser dose no longer results in acceptable postharvest N levels and the 200 kg N ha^{-1} application only in 35 % of the cases. Corrections for the two other soils, again taking the 50 % cut-offs, are 5 and 3 kg N ha^{-1} m^{-1} for soils 2 and 3 respectively resulting in 42 and 49 kg N ha^{-1} m^{-1} for soils 2 and 3.

The cumulative distribution functions of potato production are presented in Figure 4.7. For all soils higher N doses result in higher production levels. Overall production levels are low relatively low for soil 1 followed by soils 3 and 2. The production increase for the high fertiliser levels (200 kg ha^{-1}) is low for all three soils. Soil 1 reveals some variation for the high fertiliser doses and overall temporal variability is high for this soil as indicated by the large range (5.5 ton dm ha^{-1}). Only after reducing the dose with to 200 kg N ha^{-1}, postharvest N values for soils 2 and 3 are within acceptable limits. For soil 1 the reduction needed to reach acceptable postharvest N levels is 75 kg N ha^{-1} to 175 kg N ha^{-1}. Reduced fertiliser input will result in a lowering of production levels. The reduction in potato production is highest for soil 1 and only minor for the other two soils (figures 4.4C and 4.7). The average yield drop for soil 1 (Figure 4.4C) is about 0.5 ton dm ha^{-1} and for soils 2 and 3: 0.1 ton dm ha^{-1}. The temporal risk (figure 4.7) is also higher for soil 1. This is the price that has to be paid to reach an environmentally acceptable production system.

By taking the 50 % cut-off in figure 4.6, extreme situations in occasional leaching during the growing season are ignored. Reducing the risk would result in lower postharvest N profiles and further lowering of the production levels. For soil 1 the leaching during the "dry" growing season in some cases even exceeds the 42 kg N ha^{-1} limit (figure 4.6). When opting for zero risk (taking the 100 % cut-off

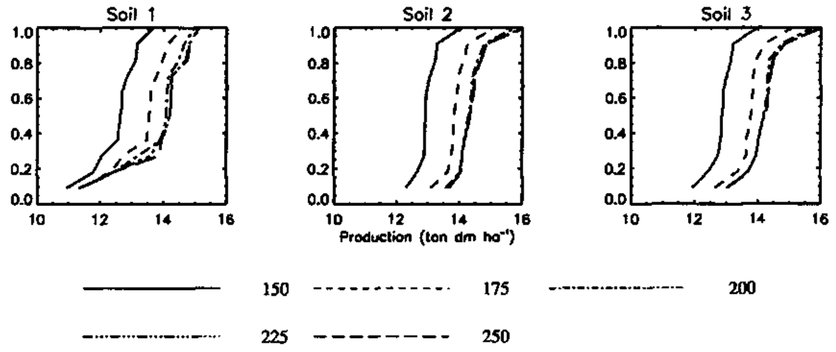

Figure 4.7: *Cumulative distribution functions of potato production for the different fertiliser doses [kg N ha^{-1}] for the three soils.*

value) this would mean excluding all units 1 and 2 from production. For unit 2 the postharvest threshold would drop to 27 kg N ha^{-1} m^{-1} which is in all cases exceeded (Figure 4.5). Only unit 3 is stable with respect to production and leaching during the "dry" season. The no risk threshold for this unit would drop to 42 kg N ha^{-1} m^{-1} which still allows fertiliser rates of 200 kg N ha^{-1} (Figure 4.5).

The N fertiliser recommendation for potato is based on a single dose application. This doesn't allow farm management to adjust fertiliser management as the crop develops. A first application, base dressing, followed by one or more applications thereby adding control points to adjust fertiliser management will become standard in site specific management. By using split applications in combination with simulation models the crop requirements and involved leaching risks can be assessed on a shorter time frame and can therefore be more accurate.

When using split applications we need to consider that half of the required nitrogen is already taken up when only a quarter of the final crop mass has been produced to according the relation between produced biomass and N concentration (Greenwood et al., 1985, 1990). Decision support for fertiliser management should therefore focus on the time frame in which this 25 % of the final crop is formed.

The WAVE model doesn't allow N-uptake higher than the required N. The results shown are in this respect worst-case scenarios; in reality the actual uptake may be higher than the required uptake resulting in lower postharvest N contents. This may, in fact, enhance the differences between the units.

Conclusions

1. Representative profiles of functional mapping units for precision agriculture can be selected using quantitative criteria.

2. Soil quality indicators, as discussed and defined in this paper, are needed to guide farm management.

3. Fertiliser management during the growing season should focus on postharvest soil N contents which mainly governs leaching during the "wet season" under Dutch conditions.

Chapter 5

Conclusions

1. Variability of physical soil properties has a significant impact on both potato production and nitrate leaching. Distinction of functional soil layers allowed the soil–physical characterisation of a highly variable field with stratified soils.

2. The simulation model WAVE could be used successfully to quantify both crop production and the assocaited nitrate leaching for point data. Geostatistical interpolation techniques allowed the step from points to areas.

3. Temporal variation could be expressed by exploratory running of the WAVE model using weather data for a number of years.

4. Adjusting N fertiliser application, taking into account spatial variable conditions, can significantly reduce leaching without lowering the production level.

5. A comparison of maps showing yields and leaching for a number of years, has indicated that soil related patterns can be defined for a field that are stable in space and time.

6. Definition of threshold values for nitrate leaching should reflect spatial and temporal variation by defining such thresholds in terms of probability of exceedance under various weather conditions.

7. Selection of representative profiles for mapping units to be used for precision agriculture, can be done based on quantitative criteria.

8. Under Dutch climatic conditions, the N content at the end of the growing season defines nitrate leaching during the winter period. Variable critical N

contents, based on a predefined threshold–value, within a field can be defined using simulation. These critical N contents are a guideline for fertiliser practices in the growing season.

Future research

Increasingly technology seems to be the driving force in site specific management. This is both a blessing and a curse. Using GPS, Remote sensing, yield mapping etc. etc. spatially variable conditions of e.g. crop development can be visualised providing a direct link with farm management. Or as someone once said: "For a farmer to see the first yield map of his field is an emotional experience". But too much emphasis on measuring techniques may distract farming systems research from the major questions: "where", "when" and "how much".

To be able to address these questions process-oriented quantitative research is needed. Simulation models can play a central role in systems analysis but further development of models is needed. Effects of split N applications or organic fertilisers on crop growth and, more important soil and crop quality are still not clear. This also implies that well documented measured data are needed to verify model concepts. Field experiments in combination with simulation models can provide a better understanding of the underlying processes.

The incorporation of models in decision support systems is needed to provide insight into possible economical, environmental and even sociological effects of management decisions. Here, models can also become a communication tool between the various disciplines. Interdisciplinarity is the main ingredient of any decision support system for precision agriculture. For effective communication, functional or empirical models based on data derived from mechanistic models may prove to be a better tool than the complex mechanistic models themselves.

From field to farm level is still a large step. A new interdisciplinary project located in Voorne Putten at the Van Bergeijk farm addresses problems at farm level in the context of developing a decision support system for precision agriculture.

Bibliography

Addiscott, T. M. (1993). Simulation modeling and soil behavior. *Geoderma*, 60:15 – 41.

Beek, K. J., Burrough, P. A., and McCormack, D. E., editors (1987). *Quantified Land Evaluation Procedures*. ISSS/SSSA. Proc. of a workshop. 27 April - 2 May 1986. Washington D. C. ITC-Publication no. 6.

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

Birrel, S. J., Borgelt, S. C., and Sudduth, K. A. (1995). *Crop Yield Mapping: Comparison of Yield Monitors and Mapping Techniques*, pages 15 – 32. In Robert et al. (1995a). Spec. Publ.

Booltink, H., Thornton, P., Verhagen, J., and Bouma, J. (1997). Application of simulation models and wheather generators to optimize farm management strategies. In Robert et al. (1997). Spec. Publ.

Booltink, H. W. G. (1994). Field-scale distributed modeling of bypass flow in a heavily textured clay soil. *Journ. of Hydrology*, 163:65 – 84.

Booltink, H. W. G., Bouma, J., and Gimenez, D. G. (1991). A suction crust infiltrometer for measuring hydraulic conductivity of unsaturated soil near saturation. *Soil Sci. Soc. Am. J.*, 55:566 – 568.

Booltink, H. W. G. and Verhagen, J. (1997). *Using Decision Support Systems to Optimize Barley Management on Spatial Variable Soil*, pages 219 – 233. Volume 2 of Kropff et al. (1997).

Bouma, J. (1989). *Using soil survey data for quantitative land evaluation*, pages 177 – 213. Volume 9 of Stewart (1989).

Bouma, J. (1992). *Effect of soil structure, tillage and aggregation upon soil hydraulic properties*, pages 1 – 37. In Wagenet et al. (1992).

Bouma, J. (1994). Sustainable land use as a future focus of pedology. *Soil Sci. Soc. Amer. J.*, 58:645 – 646.

Bouma, J. (1997a). *Precision agriculture: introduction to the spatial and temporal variability of environmental quality.* CIBA-EERO Symposium on Precision agriculture. Bock, G. and Lahe, J., editors.

Bouma, J. (1997b). Soil environmental quality: A european prespective. *J. of Environ.. Qual.*, 26:26 – 31.

Bouma, J., Booltink, H. W. G., and Finke, P. A. (1996). Use of soil survey data for modeling solute transport in the vadose zone. *J. of Environ. Qual.*, 25:519 – 526.

Bouma, J., Brouwer, J., Verhagen, A., and Booltink, H. W. G. (1995). Site specific management on field level: high and low tech approaches. pages 453 – 475, Dordrecht, the Netherlands. Kluwer Publ.

Bouma, J., Brouwer, J., Verhagen, J., and Powell, J. M. (1997). Using systems approaches for targetting site-specific management on field level. In Kropff et al. (1997), pages 25 – 36.

Bouma, J. and Hoosbeek, M. R. (1996). *The contribution and importance of soil scientists in interdisciplinary studies dealing with land.* In Wagenet and Bouma (1996). Special publication 45, Soil Sci. Soc. Am.

Bouma, J. and Van Lanen, H. A. J. (1987). Transfer functions and threshold values: from soil characteristics to land qualities. In Beek et al. (1987), pages 106 – 111. Proc. of a workshop. 27 April - 2 May 1986. Washington D. C. ITC-Publication no. 6.

Breeuwsma, A., Wösten, J. H. M., Vleeshouwer, J. J., Van Slobbe, A. M., and Bouma, J. (1986). Derivation of land qualities to assess environmental problems form soil surveys. *Soil Sci. Soc. Amer. J.*, 50 (1):186 – 190.

Bryant, R. B. and Arnold, R. W., editors (1994). *Quantitative modelling of soil forming processes.* Soil Sci. Soc. of America, Madison WI. Spec. Publication 39.

Burrough, P. A. (1993.). Soil variability revisited. *Soils and Fert.*, 56(5):529 – 562.

Corré, W. J. (1994). *Bepaling van de hoeveelheid minerale stikstof in de bodem in het najaar als instrument voor het te voeren stikstof beleid.* Akkerbouwgewassn en vollegrondsgroente, AB-DLO rapport 21.

Davis, C. D. (1986). *Statistics and data analysis in geology - second edition.* John Wiley and Sons, New York.

De Steenhuijsen Piters, B. (1995). *Diversity of fields and farmers: explaining yield variations in northern Cameroon.* PhD thesis, Wageningen Agricultural University, Wageningen, the Netherlands.

De Wit, C. T. (1992). Resource use efficiency in agriculture. *Agricultural Systems*, 40:125 – 151.

De Wit, C. T. and Van Keulen, H. (1987). Modelling production of field crops and its requirements. *Geoderma*, 40:253 – 265.

Deutsch, C. V. and Journel, A. G. (1992). GSLIB *Geostatistical Software Library and User's Guide.* Oxford University Press, New York.

Diels, J. (1994). *A validation procedure accounting for model input uncertainty: methodology and application to the* SWATRER *model.* PhD thesis, Catholic University Leuven, Leuven.

Dierckx, J., Belmans, C., and Pauwels, P. (1986). SWATRER, *a computer package for modelling the field water balance. Reference manual.* Leuven.

Etchevers, J. D., Aguilar, A., Núñez, R., Alcantar, G., and Sanchez, P., editors (1994). *Proc. 15th World Congress of Soil Science, July 10 – 16, 1994. Acapulco, Mexico*, volume 6a.

FAO (1993). *FESLM: An International Framework for Evaluating Sustainable Land Management.* FAO, Rome, Italy. World Resources Report 73.

Feddes, R. A., Kowalik, P. J., and Zaradny, H. (1978). *Simulation of field water use and crop yield. Simulation monographs.* PUDOC, Wageningen.

Finke, P. A. (1992). *Spatial variability of soil structure and its impact on transport processes and some associated land qualities.* PhD thesis, Wageningen Agricultural University, Wageningen, the Netherlands.

Finke, P. A. (1993). Field scale variability of soil structure and its impact on crop growth and nitrate leaching in the analysis of fertilizing scenarios. *Geoderma*, 60:89 – 109.

Finke, P. A. and Bosma, W. J. P. (1993). Obtaining basic simulation data for a heterogeneous field with stratified marine soils. *Hydrological Processes*, 7:63 – 75.

Franzen, D. W. and Peck, T. R. (1995). *Sampling for site-specific fertilizer application.* In Robert et al. (1995a). Spec. Publ.

Fresco, L. O., Stroosnijder, L., Bouma, J., and Van Keulen, H., editors (1995). *The future of the land. Mobilising and integrating knowledge for land use options.* John Wiley & Sons, Chichester - New York - Brisbane - Toronto - Singapore.

Greenwood, D. J., Lemair, G., Gosse, G., Cruz, P., Draycott, A., and Neeteson, J. J. (1990). Decline in percentage N of C3 and C4 crops with increasing plant mass. *Annals of Botany*, 66:425 – 436.

Greenwood, D. J., Neeteson, J. J., and Draycott, A. (1985). Response of potatoes to N fertilizer: quantitative relations for components of growth. *Plant and Soil*, 85:163 – 183.

Heuvelink, G. B. M. (1993). WLSFIT manual. Technical report, University of Amsterdam, Amsterdam.

Hoosbeek, M. R. and Bryant, R. B. (1992). Towards the quantitative modeling of pedogenesis - a review. *Geoderma*, 55:183 – 210.

Hutson, J. and Wagenet, R. J. (1992). LEACHN, a process-based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Technical report, Cornell University, Ithaca, NY.

IKC (1993). *Stikstofbemestingsrichtlijnen voor de akkerbouw en de groenteteelt in de vollegrond.* Ministerie van Landbouw, Natuurbeheer en Visserij. Informatie en Kenis Centrum Akker- en Tuinbouw.

Journel, A. G. and Huijbergts, C. J. (1978). *Mining Geostatistics*. Academic Press, London.

Kropff, M. J., Teng, P. S., Aggarwal, P. K., Bouma, J., Bouman, B. A. M., Jones, J. W., and Van Laar, H. H., editors (1997). *Systems Approaches for Agricultural Development* Applications of systems approaches at the field level. Proceedings of the second international symposium on systems approaches for agricultural development, held at IRRI, Los Baños, Philippines, 6 – 8 December 1995, volume 2, Dordrecht/Boston/London. Kluwer Academic Publishers.

Mausbach, M. J. and Wilding, L. P., editors (1991). *Spatial variability of soils and land forms*. Soil Sci. Soc. of America, Madison WI. Spec. Publication 28.

Murphy, D. P., Haneklaus, S., and Schnug, E. (1994a). Innovative soil sampling and analysis procedures for the local resource management of agricultural soils. In Etchevers et al. (1994), pages 613 – 631.

Murphy, D. P., Schnug, E., and Haneklaus, S. (1994b). *Yield mapping- A guide to improved techniques and strategies*, pages 33 – 48. In Robert et al. (1995a). Spec. Publ.

Neeteson, J. J. and Wadman, W. P. (1987). Assessment of economic optimum application rates of fertilizer n on the basis of response curves. *Fertilizer Research*, 12:37 – 52.

Olea, R. A. (1991). *Geostatistical Glossary and Multilingual Dictionary*. International association for Mathematical geology studies in mathematical geology No.3.

Pierce, F. J. and Sadler, E. J., editors (1997). *The state of site-specific management for agriculture.* ASA, CSSA, and SSSA, Madison, WI. ASA Misc. Publ.

Rabbinge, R. and Van Ittersum, M. K. (1995). *Tension between aggregation levels*, chapter 3, pages 31 – 40. In Fresco et al. (1995).

Rabbinge, R., Van Laar, H. H., and Ward, S., editors (1988). *Simulation and systems management in crop protection.* PUDOC, Wageningen.

Rassenlijst (1995). 70e beschrijvende rassenlijst voor landbouwgewassen 1995. Technical report, Commissie voor de samenstelling van de Rassenlijst voor Landbouwgewassen.

Rawlins, S. L., Campbell, G. S., Campbell, R. H., and Hess, J. R. (1995). *Yield mapping of potato.* In Robert et al. (1995a). Spec. Publ.

Reetz, F. R. and Fixen, P. E. (1995). Economic analyses of site specific nutrient management systems. In Robert et al. (1995a), pages 742 – 752. Spec. Publ.

Robert, P. C., Rust, H., and Larsen, W. E., editors (1993). *Site specific crop management: a workshop on research and development issues. April 14 – 16, 1992. Minneapolis, MN.*, Madison, Wis, USA. Soil Sci. Soc. of America. Spec. Publ.

Robert, P. C., Rust, H., and Larsen, W. E., editors (1995a). *Site specific management for agricultural systems. Second International Conference. March 27 – 30, 1994. Minneapolis, MN.* Soil Sci. Soc. of America, Madison, Wis, USA. Spec. Publ.

Robert, P. C., Rust, H., and Larsen, W. E., editors (1997). *3^{rd} International Conference on precision farming. June 23 – 26, 1996. Minneapolis, MN.*, Madison, Wis, USA. Soil Sci. Soc. of America. Spec. Publ.

Robert, P. C., Seeley, M. W., Anderson, J. L., Cheng, H. H., Lamb, J. A., Moncrief, J. F., Rehm, G. E., Rosen, C. J., and Schmitt, M. A. (1995b). *The Minnesota precision farming initiative*. In Robert et al. (1995a). Spec. Publ.

Sadler, E. J. and Russell, G. (1997). *Modeling Crop Yield for Site-Specific Management*, pages 69–79. In Pierce and Sadler (1997). ASA Misc. Publ.

Soil Survey Staff (1975). *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*. USDA SCS, printing Office, Washington DC. Agric. Handbook 436. US Gov't.

Spitters, C. J. T. and Schapendonk, A. H. C. M. (1990). Evaluation of breeding strategies for drougth tolerance in potato by means of crop growth simulation. *Plant and Soil*, 123:193 – 203.

Spitters, C. J. T., Van Keulen, H., and Van Kraailingen, D. W. G. (1988). *A simple but universal crop growth simulation model,* SUCROS87, pages 87 – 98. In Rabbinge et al. (1988).

Stein, A., Hoogerwerf, M., and Bouma, J. (1988). Use of soil map delineations to improve (co)kriging of point data on moisture deficits. *Geoderma*, 43:163 – 177.

Stewart, B. A., editor (1989). *Advances in Soil Science*, volume 9. Springer Verlag, New York.

Teng, P. S. and Penning de Vries, F. W. T. (1992). Systems approaches for agricultural development. *Agricultural Systems*, 40:1 – 3.

Van Breemen, N. and Bouma, J. (1988). *In het aardedonker. Terug naar de toekomst*. Inaugerele rede, Wageningen.

Van Dam, J. C., Stricker, J. N. M., and Droogers, P. (1994). Inverse method to determine soil hydraulic functions from multistep outflow experiments. *Soil Sci. Soc. Am. J.*, 58:647 – 652.

Van der Ploeg, R. R., Ringe, H., and Muchalla, G. (1995). Late fall site-specific soil nitrate upper limits for groundwater protection purposes. *J. of Environ. Qual.*, 24:725 – 733.

Van Lanen, H. A. J., Bannink, M. H., and Bouma, J. (1986). Use of simulation to assess the effect of different tillage practices on land qualities of a sandy loam soil. *Soil Tillage Research*, 10:347 – 361.

Van Lanen, H. A. J., Reinds, G. J., Boersma, O. H., and Bouma, J. (1992). Impact of soil management systems on soil structure and physical properties in a clay loam soil and the simulated effects on water deficits, soil aeration and workability. *Soil and Tillage Research*, 23:203 – 220.

Van Noodwijk, M. and Wadman, W. P. (1992). Effects of spatial variability of nitrogen supply on envirnomentally acceptable nitrogen fertilizer application rates to arable crops. *Netherlands Journal of Agricultural Science*, 40:51 – 72.

Van Uffelen, C. G. R., Verhagen, J., and Bouma, J. (1997). Comparison of simulated crop reaction patterns as a basis for site specific management. *Agricultural Systems*, 54:207 – 222.

Vanclooster, M., Viane, P., Diels, J., and Christiaens, K. (1994). WAVE *a Mathematical Model for Simulating Water and Agrochemicals in the Soil and Vadose Environment - Reference & User's Manual (Release 2.0)*. Institute for Land and Water Management, Leuven.

Verhagen, A., Booltink, H. W. G., and Bouma, J. (1995a). Site specific management: balancing production and environmental requirements at farm level. *Agricultural Systems*, 49:369 – 384.

Verhagen, J. (1997). Site specific fertiliser application for potato production and effects on N-leaching using dynamic simulation modelling. *Agriculture, Ecosystems & Environment.* (in press).

Verhagen, J. and Bouma, J. (1997). Defining threshold values: a matter of space and time. *Geoderma.* Submitted.

Verhagen, J., Verburg, P., Sybesma, M., and Bouma, J. (1995b). *Terrain modelling as a basis for optimal agroecological land managment using dynamic simulation*, pages 229 – 250. In Robert et al. (1995a). Spec. Publ.

VROM (1989). *Nationaal Milieubeleidsplan.* Ministerie van Volkshuisvesting, Ruimtelijke Orening en Milieubeheer. Tweede Kamer, vergaderjaar 1989-1990.

Wagenet, R. J. and Bouma, J., editors (1996). *The role of soil science in interdisciplinary research.* SSSA, Madison, WI. Special publication 45, Soil Sci. Soc. Am.

Wagenet, R. J., Bouma, J., and Grossman, R. B. (1991). *Minimum data sets for use of Taxonomic information in soil interpretive models*, pages 161 – 182. In Mausbach and Wilding (1991). Spec. Publication 28.

Wagenet, R. J., Bouma, J., and Hutson, J. L. (1994). *Modeling water and chemical fluxes as driving forces of pedogenesis*, pages 17 – 37. In Bryant and Arnold (1994). Spec. Publication 39.

Wagenet, R. S., Baveye, P., and Stewart, B. A., editors (1992). *Advances in Soil Science. Interacting Processes in Soil Science*. Lewis Publishers, London.

Webster, R. and Oliver, M. A. (1990). *Statistical Methods in Soil and Land Resource Survey*. Oxford University Press, New York.

Wilding, L. P., Bouma, J., and Goss, D. (1994). *Impact of spatial variability on modeling*, pages 61 – 77. In Bryant and Arnold (1994). Spec. Publication 39.

Wösten, H. J. W., Bouma, J., and Stoffelsen, G. H. (1985). The use of soil survey data for regional soil water simulation models. *Soil Sci. Soc. Amer. J.*, 49:1238 – 1245.

Wösten, J. H. M., Bannink, M. H., De Gruijter, J. J., and Bouma, J. (1986). A procedure to identify different groups of hydraulic-conductivity and moisture-retention curves for soil horizons. *Journal of Hydrology*, 86:133 – 145.

Summary

This thesis focuses on the optimisation of N fertiliser application, taking into account spatially variable soil conditions. Spatial soil variability effects both crop production and nitrate leaching. Site specific management tries to address spatially variable conditions. Research on site specific management was done for a field on the experimental farm "the Van Bemmelenhoeve" in the north western part of the Netherlands.

In summary the objectives of this study were:

1. To measure spatial and temporal variability of soil physical properties, yield and N for a farm field.

2. To quantify spatial and temporal variability, using simulation modelling and geostatistics, of:

   (a) crop production and nitrate leaching.

   (b) effects of N fertiliser management on production and leaching.

3. To identify areas in the field with comparable behaviour with respect to production and leaching, considering the effects of multi-year weather variation in both the growing season and the season with precipitation surplus.

4. To define representative profiles for the identified map units using two land quality indicators: nitrate leaching and crop production.

Chapter 2 serves as an introduction to the study area. The spatial variation of potato production, total N and soil physical properties are quantified. Potato yields, measured in 65 small plots varied between 30 and 45 tons ha^{-1}, while yields of commercially attractive large potatoes varied between 3 and 15 tons ha^{-1}. Such differences are economically significant for a farmer. Total N in the early part of the growing season varied between 21 and 53 kg ha^{-1}. When compared with recommended fertiliser rates obtained from one mixed sample for the entire field, local over- and underfertilization can be demonstrated. These are bound to lead to groundwater pollution and inefficient production. Modeling can be used to balance production and environmental aspects in a quantitative manner. Exploring the spatial and temporal behaviour of the field using simulation models and geostatistics is shown to be an attractive approach in agrosystems research.

In chapter 3 the implications on farm management of spatially variable soil conditions are discussed. Maps displaying relevant soil variability are needed to guide site specific practices. In section 3.1 simulated water-limited yield patterns are shown to be stable in space and time. A "prototype" pattern is derived from seven simulated water-limited yield patterns. This "prototype" can be used as a base map for site specific management. The effects of site specific fertiliser application on potato production and nitrate leaching are studied using dynamic simulation in section 3.2. Simulations show that the recommended fertiliser dose for 1994 was too high for the entire field. Fine-tuning of the fertiliser application using the "prototype" pattern was succesful in maintaining high production levels and reducing leaching of nitrate to the groundwater. Leaching of nitrate occurs mainly during the "wet" winter season (September 15 – April 15). The amount of nitrate leached during the "wet" period is dictated by postharvest soil N conditions. In section 3.3 the soil-N contents are defined for 65 soil profiles corresponding with a predefined threshold value for nitrate leaching to the ground water. Leaching was calculated for 5 different N profiles at the beginning of the wet period for 20 years. For the given initial N range (15 - 120 kg N ha^{-1} m^{-1}) space time relations for the defined period are linear. The required N profile at September 15 is calculated using three risk levels of exceeding these thresholds. Spatial interpolation of the required N profiles results in N target maps which can be used to focus and evaluate N fertiliser management.

Farm management should focus N fertiliser practices during the "dry" growing season on post harvest soil N conditions discussed above. In chapter 4 the consequences of this approach are calculated for the experimental field. Spatial variation is characterised using three representative profiles for three subareas within the field. The three representative profiles for the soil units are identified and tested for internal homogeneity, by considering temporal variability of nitrate leaching during the "wet" season. Carry-over effects of N fertiliser management during the growing season to the "wet" season were quantified for the three representative profiles by simulations for an 11 year period. Thus, a probabilistic interpretation of five fertiliser scenarios resulted in recommended site-specific N fertiliser applications that allow high levels of potato production without exceeding the legal threshold for nitrate leaching. The latter is expressed in terms of probability of exceedance. Possibilities for farm management to focus fertiliser application during the growing season on post harvest N are discussed. Reducing nitrate losses to the environment by means of lower N fertiliser rates, taking into account spatial and temporal variation, is feasible under the studied conditions for the experimental field without significant losses in potato production.

Samenvatting

Dit proefschrift richt zich op de optimalisatie van stikstofbemesting, waarbij rekening gehouden wordt met de ruimtelijke variabiliteit van de bodem. Ruimtelijke bodemvariabiliteit beinvloedt de gewasproductie en de uitspoeling van nitraat. Locatiespecifiek beheer probeert hiermee rekening te houden. Het onderzoek is verricht op een veld op de proefboerderij "de van Bemmelenhoeve" gelegen in het noordwesten van Nederland.

Doelstellingen van deze studie zijn:

1. Het meten van de ruimtelijke en temporele variabiliteit van bodemfysische eigenschappen, oogst en nitraatuitspoeling voor het veld.

2. Het kwantificeren, met behulp van simulatie modellen en geostatistiek, van de ruimtelijke en temporele variabiliteit, van:

    (a) gewasproductie en nitraatuitspoeling.

    (b) effecten van stikstofbemesting op productie en uitspoeling.

3. Het, binnen het veld, identificeren van gebieden met vergelijkbaar gedrag ten aanzien van productie en uitspoeling, waarbij rekening gehoudend wordt met de variatie in weersomstandigheden in het "droge" groeiseisoen en het seisoen met een neerslag overschot.

4. Het definiëren van representatieve profielen voor de geïndentificeerde gebieden met behulp van twee landkwaliteitsindicatoren nl. nitraatuitspoeling en gewasproductie.

Hoofdstuk 2 is een introductie van het studie gebied met een kwantificering van aardappelproductie, totaal N en bodemfysische eigenschappen. De aardappelopbrengsten, gemeten in 65 plotjes, varieerden tussen de 30 en 45 ton ha^{-1}, terwijl die van commercieel aantrekkelijke aardappels varieerden tussen de 3 en 15 ton ha^{-1}. Deze verschillen zijn van economisch belang voor de landbouwer. Totaal N (gemeten tot 1 meter) in het begin van het groeiseisoen lag tussen de

21 en 53 kg ha^{-1} m^{-1}. Bemestingsadviezen gebaseerd op een mengmonster voor het gehele veld leidden onvermijdelijk tot lokale over- en onderbemesting met als gevolg: grondwaterverontreining en inefficiënte productie. Simulatie kan gebruikt worden bij het op een kwantitative manier balanceren van productie en milieuaspecten. Bij agrosysteem onderzoek is het onderzoeken van het ruimtelijk en temporeel gedrag van het veld met behulp van simulatie modellen en geostatistiek is een aantrekkelijke benadering gebleken.

In hoofdstuk 3 worden de implicaties van de ruimtelijke bodemvariabiliteit op de bedrijfsvoering behandeld. Om lokatiespecific te kunnen werken zijn kaarten nodig, die de relevante bodem variatie weergeven. In sectie 3.1 wordt getoond dat gesimuleerde patronen van watergelimiteerde productie stabiel zijn in ruimte en tijd. Een "prototype" patroon is uit de zeven gesimuleerde water gelimiteerde opbrengst patronen geextraheerd. Dit "prototype" is bruibaar als basiskaart voor lokatie specifiek beheer. De effecten van lokatiespecifiek bemesten op aardappelproductie en de nitraatuitspoeling zijn bestudeerd in sectie 3.2. Simulaties laten zien dat de aanbevolen hoeveelheid stikstof te hoog was voor het gehele veld. Een verfijning van de bemestingsgift, gebaseerd op het "prototype" patroon, was succesvol wat betreft handhaving van een hoge productie en reductie van de nitraatuitspoeling. Nitraatuitspoeling vindt hoofdzakelijk plaats tijdens het "natte" winter seisoen (15 september – 15 april) en wordt bepaald door aanwezige hoeveelheid stikstof aan het eind van het groeisesioen. In sectie 3.3 worden de bodemstikstof profielen gedefinieerd voor 65 bodem profielen waarij uitgegaan wordt van een drempelwaarde voor nitraat emissie naar het grondwater. Uitspoeling is berekend voor 5 stikstofprofielen aan het begin van het groeiseisoen voor 20 jaren. Binnen de gekozen range van (15 – 120 kg N ha^{-1} m^{-1}) zijn de ruimte-tijd-relaties voor de gedefineerde periode lineair. Het gewenste stikstofprofiel voor 15 september is berekend voor drie risico-niveaus voor wat betreft overschrijding van de drempelwaarde. De ruimtelijke interpolatie van de gewenste stikstofprofielen resulteert in stikstof kaarten, die van dienst kunnen zijn om het stikstofbemestingsplan te sturen en te evalueren.

Het bemestingsplan dient, zoals hierboven beschreven, gedurende het "droge" seizoen door het bedrijfsmanagment af gestemd te worden op de rest-stikstof aan het eind van het groeiseizoen. In hoofdstuk 4 worden de gevolgen van deze benadering doorgerekend voor het veld. De ruimtelijkevariatie is gekarakteriseerd met behulp van drie representatieve profielen voor de drie bodemeenheden in het veld. De homogeniteit van deze 3 bodemeenheden is getest, gebruik makend van de temporele variabiliteit van de nitraatuitspoeling tijdens het "natte" seizoen. De interpretatie van vijf bemestingsscenarios resulteerde in lokatie specifieke bemestingsadviezen, waarbij er een hoge aardappel productie is zonder dat de drempelwaarde voor de nitraatuitspoeling overschreden wordt. Veder worden er mogenlijkheden voor de bedrijfsvoering, om de bemestingsgift af te stemmen op de rest-stikstof aan het einde van het groeiseizoen, besproken. Reductie van nitraatemissies naar het milieu door het verlagen van stikstofgiften, waarbij rekening gehoudend wordt met de ruimtelijke en temporele variabiliteit is haalbaar gebleken voor het studie gebied zonder dat er een significante produktiederving optreedt.

Curriculum Vitae

Jan (Adrianus) Verhagen was born on January 28 1964 in Gemonde (Sint Michielsgestel), the Netherlands. He started his study on the College of Land and Water Management in 1982 and graduated in July 1986. From July till November 1986 he traveled in Indonesia. In December 1986 he started to work at the International Soil Reference and Information Center. From December 1988 till December 1989 he was involved in soil correlation and soil database management for the Land Resource and Evaluation Project in Bogor, Indonesia. From December 1989 till July 1990 he worked on the development of a wetland database for the Asian Wetland Bureau in Bogor. In August 1990 he returned to the Netherlands and started his MSc study at the department of Soil Science and Geology in Wageningen, he graduated in July 1992. In April 1993 he started his PhD research at the department of Soil Science and Geology. From September 1997 he is employed by the Research Institute for Agrobiology and Soil Fertility in Wageningen.

In 1993 he married Rachmawati Sri Mulyati Saloh. They have two children: Anna Eka Juanti and Wim Jonas Sangkuwung.