SOIL PROCESSES AS A GUIDING PRINCIPLE IN PRECISION AGRICULTURE

A Case Study for Dutch Arable Farming

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A Case Study for Dutch Arable Farming

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Stellingen

1. De introductie van precisielandbouw zal in Nederland eerder worden gedreven door milieuvoordelen dan door economische voordelen.
   Dit proefschrift

2. Voor de overgang naar precisielandbouw is een bodemkartering op bedrijfsniveau niet alleen noodzakelijk, maar ook betaalbaar.
   Dit proefschrift

3. Het merendeel van de bodemvariabiliteit die op bedrijfsniveau wordt aangetroffen kan met een beperkt aantal managementeenheden worden beschreven. De toegevoegde waarde van verdere verfijning wordt daarmee discutabel.
   Dit proefschrift

4. Simulatiemodellen vormen een essentieel hulpmiddel bij het afleiden van functionele bodemeigenschappen en het 'vertalen' van deze eigenschappen naar richtlijnen voor precisielandbouw. De beschikbaarheid van zogenaamde 'pedotransfer functies' maakt het verkrijgen van de benodigde invoerparameters daarbij een stuk eenvoudiger.
   Dit proefschrift

5. Zolang de technologie en toepassing van precisielandbouw nog niet zijn uitgekristalliseerd – en dit proefschrift vormt hiertoe slechts een aanzet – is het gevaarlijk te reppen over de vermeende kosten en baten.

6. Ontwikkelingen rondom precisielandbouw behelzen op de keper beschouwd niets meer en niets minder dan de grootschalige intrede van informatie- en communicatietechnologie in de grondgebonden landbouw.

7. Er zijn relatief eenvoudige vormen van precisielandbouw die technisch en economisch haalbaar lijken. De vraag 'wel of geen precisielandbouw' moet daarom niet als een zwart-wit vraagstuk worden benaderd.

8. In zijn algemeenheid geldt (dus ook voor de landbouw): kan het beter, dan moet het ook beter. De wetenschap dient de mogelijkheden tot verbetering duidelijk in kaart te brengen, op basis waarvan politieke besluitvorming over de invoering kan plaatsvinden.

9. Het uitvoeren van onderzoek in een praktijkomgeving – ook wel prototyping genoemd – staat niet op gespannen voet met wetenschappelijke kwaliteit. Integendeel, als de onafhankelijkheid van de onderzoeker wordt gewaarborgd kan een duidelijke meerwaarde worden gecreëerd.

10. Wachtlijsten in de zorg zijn noodzakelijk om vraag en aanbod op elkaar af te stemmen. Momenteel is de wachtlijstomvang echter in veel gevallen onacceptabel.

11. In een wijk als Lombok, Utrecht laat de multiculturele samenleving zich bij uitstek genieten in het (afhaal)restaurant.

12. De gemiddelde toerist reist steeds verder, maar ziet niets meer dan voorheen.

Stellingen behorende bij het proefschrift van Jeroen van Alphen getiteld *Soil processes as a guiding principle in precision agriculture.* Wageningen, 20 februari 2002.

VOORWOORD

Het schrijven van een proefschrift wordt door velen beschouwd als een eenzame aangelegenheid. Hoewel dat voor enkelen zeker het geval zal zijn, is mijn ervaring is een geheel andere. Binnen het laboratorium voor bodemkunde en geologie, waar ik in 1997 als AIO aan de slag ging, bestond een vrij omvangrijke groep onderzoekers die zich bezig hielden met de precisielandbouw. Gedurende mijn verblijf is deze groep - ondanks een komen en gaan van promovendi - blijven bestaan. Het toetsen van ideeën, het laten becommentariëren van artikelen of gewoon een goed gesprek waren immer binnen handbereik. Graag wil ik van de gelegenheid gebruik maken om hier een aantal personen te bedanken.

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Jetse Stoorvogel is om meer dan inhoudelijke redenen een belangrijke speler geweest. Als co-promotor was Jetse de ideale sparringpartner, hetgeen tot uitdrukking komt in zijn talrijke co-auteurschappen (Jetse is mede-auteur van vier artikelen in dit proefschrift). Als collega en vriend was Jetse de gastheer van menig overvloedige lunch, koffie met gebak of een lekker borrel. Jetse, bedankt voor de samenwerking en je gezelligheid.

Harry Booltink was nauw betrokken bij de opstartfase, waarin bodemfysische metingen en de initiële worstelingen met het simulatiemodel centraal stonden. Harry treedt op als co-promotor en is mede-auteur van één van de artikelen in dit proefschrift. Harry, hartelijk dank voor je bijdrage.

Piet Peters heeft een grote bijdrage geleverd aan het veldwerk en een aantal bodemfysische bepalingen verricht. Met name onze talloze reizen naar Zuidland - weer of geen weer - zullen me bijblijven. Piet, het veldwerk was altijd iets om naar uit te kijken!

Binnen het laboratorium voor bodemkunde en geologie zijn nog diverse andere personen betrokken geweest: Jan Verhagen en Peter Droogers als directe voorgangers en vraagbaken, Eef Velthorst, Barend van Lagen en Neeltje Nakken voor chemische analyses, Dennis Walvoort als 'lunchkoning' en mede-congresganger en natuurlijk mijn kamergenote Mirjam Pulleman voor nuchtere reflectie.

Verder ben ik dank verschuldigd aan Jaap van Bergeijk, voormalig collega bij de vakgroep agrotechniek en fysica. Jaap was onmisbaar voor uitvoering van de veldexperimenten. Hij combineert boeren praktijkkennis met een passie voor techniek, die hij niet alleen zelf ontwikkelt maar ook altijd aan de praat weet te krijgen.

De families van Bergeijk in Zuidland mogen ook zeker niet ontbreken. Met name Jaap van Bergeijk Sr., Adam van Bergeijk en Rens van Bergeijk wil ik danken voor hun belangenloze medewerking. Ten allen tijde mochten we hun boerderij betreden voor allerhande metingen en veldexperimenten. Hun kritisch-opbouwend commentaar was van grotere waarde dan zij wellicht zelf zullen beseffen.

Tenslotte wil ik iemand bedanken, die met de afronding van dit proefschrift minimaal zo blij zal zijn als ikzelf. Renée, fijn dat je erbij was!

Jeroen van Alphen
Wageningen, januari 2002.

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CHAPTER 1

General Introduction

In the Netherlands, intensive agricultural practices have attracted much negative attention over recent years. Arable farming is associated with contamination of groundwater and surface waters through excessive leaching of nitrates and pesticides. Livestock breeding is associated with outbreak of disease (BSE, foot-and-mouth disease) and an unethical attitude towards animal welfare. The negative image of the agricultural sector originates from a shift of opinion witnessed in policy makers and society as a whole. In Western Europe, as in other developed parts of the world, food supply is no longer uncertain. In fact, food production has exceeded food consumption from the seventies of the last century onwards. In this situation the detrimental side effects of agricultural production increasingly and repeatedly draw the attention of concerned citizens and politicians.

Though consensus exists about the fact that conventional agricultural practices have many detrimental effects (Rabbinge, 1997), the change to sustainable economically viable farming systems proves to be difficult (Bouma *et al.*, 2001). Partly this may be attributed to the conservative nature of the agricultural sector, but agricultural research should also be addressed as it apparently falls short in playing its role as an effective initiator and facilitator of change. Meanwhile, Dutch policy makers have focused on the implementation of environmental laws that are essentially based on characteristic indicators for groundwater quality. This has resulted in progressively tighter restrictions on the input of N fertilisers and a consistent reduction of the number of registered pesticides. Enforcement of these laws still creates considerable problems, which is partly caused by their generic character: no provision is made for the significant variation among soil types. As this variation is well known to farmers, their affinity with the imposed rules and regulations is limited. In this thesis a different approach is followed, in which soil variability is the starting point of research, using the techniques of precision agriculture.

As a concept precision agriculture is nothing new. Back in the days of manual labour and scarce resources farmers concentrated their efforts on the areas of land that were most fertile. This is still the case for many small scale, low tech farming systems in developing countries (*e.g.*, Gandah, 1999). In developed countries precision agriculture became a realistic prospect once global positioning systems (GPS) and yield monitors became widespread. Variability within fields, reflected in the variability of crop yields, was suddenly clearly registered and visualised. The encountered variability was large enough to automatically raise the question as to how farm management could (or rather should) be adapted. Front runners in the United States and later in Europe and Australia caught on to the momentum and launched their individual research programs.

Wageningen University, mainly through the soil research group lead by J. Bouma, was among the front runners. "Fertilise the soil not the field" was already propagated in the late eighties (Van Breemen and Bouma, 1988). Since then, ongoing research has resulted in a series of PhD theses on precision agriculture in high tech (Finke, 1992 and Verhagen, 1997) and low tech (Ganda, 1999) environments. This thesis is the third in a series on precision agriculture under Dutch conditions. As such, it provides a continuation of the work of Finke and Verhagen.

The hypothesis underlying this and the earlier theses is formulated as: 'soil information is crucial to any operational, integrated system for precision agriculture'. This hypothesis is in line with the general development of precision agricultural research from being *technology driven* to becoming *information driven* (Robert *at al.* 1996, 1998, 2000). While registering variation remains important (yield maps, soil fertility maps, proximal sensing), the focus of attention has shifted towards understanding the causes of variation and, based on this understanding, defining appropriate guidelines for precision management. In a country like the Netherlands, where topography is generally absent, spatial variability is mainly soil bound. In order to switch from conventional management (with fields as the elementary management units) to precision management we therefore need to: (i) efficiently describe soil variability within fields and (ii) translate this information into concrete guidelines for precision management. Here we touch upon the objectives of this thesis:

1. Develop a methodology that efficiently describes soil variability at the within-field level. Soil variability should be described in terms of functional properties that are directly relevant to farm management operations. In other words: describe soils in terms of their water regimes, nutrient cycling and sorption characteristics rather than using traditional taxonomic properties such as texture, soil organic matter (SOM) content and colour.
2. Based on the above, develop methods to: (i) optimise the application of nitrogen (N) fertiliser and (ii) evaluate and control the environmental risks associated with pesticide use. These methods should be developed through prototyping (Vereijcken, 1997) on a commercial arable farm with ample attention for operational aspects.

The presented objectives are a step forwards from the work of Finke (1992) and Verhagen (1997). Instead of conducting research on an experimental farm, the study area is located on a commercial farm and experiments are conducted in close cooperation with the farmer. Besides the effect of mutual learning, this approach ensures an efficient evaluation of developed methods in terms of operational aspects. Another important difference relates to scale: where Finke and Verhagen concentrated on a single field, this research includes experiments on different fields and farm-level analyses of soil variability and leaching potentials. The incorporation of pesticide management (besides N fertilisation) also expands on the earlier work.

Besides differences, there are many similarities. The concept of soil functional layers with specific functional properties (*e.g.*, hydraulic characteristics) is adapted from Finke (1992). Likewise, the central role of simulation modelling marks a resemblance to the work of Verhagen (1997). In fact the same model (WAVE; Vanclooster *et al.*, 1994) is used to simulate crop growth, soil water regimes, N cycling and pesticide leaching.

The outline of this thesis is as follows:

i. Chapters 2 and 3 introduce the study area and present the methods applied to move from basic soil data, which were collected in a 1:5,000 soil survey, to simulated soil functional properties and onwards to soil functional units. These units serve as the management units for precision N management.

ii. Chapters 4 and 5 present the results of two fertiliser experiments conducted in winter wheat fields. The experiments compare conventional N fertilisation to precision management, which is based on real-time simulations of supply (N concentration in the root zone) and demand (N uptake by the crop). Spatial variability is accounted for by conducting separate simulations for each management unit.

iii. Chapter 6 presents a farm-level evaluation of pesticide leaching as affected by soil variability and weather conditions. Pesticides currently used in the study area are screened for excessive leaching (which is defined in probabilistic terms) and opportunities for improved pesticide management are discussed.

iv. Chapter 7 synthesises the above by discussing the various studies in terms of their implications for environmental regulations on groundwater quality. A clear distinction is made between threshold concentrations for nitrate (50 mg l^{-1}) and pesticides (0.1 $\mu g\ l^{-1}$) and the proxy measures (maximum N fertilisation rates, registration procedures for pesticides) that are used to enforce these thresholds.

The individual chapters have been submitted and accepted as scientific publications in international journals. Some aspects are repeated in different chapters and units may vary as different journals apply different standards. The bibliography is compiled and presented at the end of this thesis.

CHAPTER 2

Combining Pedotransfer Functions with Soil Physical Measurements to Improve the Estimation of Soil Hydraulic Properties[1]

2.1 Introduction

Simulation modelling of soil water regimes and nutrient dynamics has become an important tool in evaluating the effects of different management practices on crop yield and environmental quality (e.g. Verhagen, 1997; Verhagen and Bouma, 1997). Rapid developments in computer technology have created new opportunities to incorporate real-time data into modelling (e.g. meteorological data from fully automated on-farm weather stations). Modelling studies are no longer restricted to the evaluation of historical and/or synthetic conditions, but can provide estimates of actual conditions in the field. Van Alphen and Stoorvogel (2001[a]) used this type of information to implement precision management of N-fertiliser on a Dutch arable farm.

Availability and quality of input data are crucial factors in modelling studies. With respect to soil water regimes much depends on the accuracy of soil hydraulic properties (*i.e.* moisture retention and hydraulic conductivity curves). Hydraulic properties are conventionally derived through laboratory measurements (e.g. multistep procedure; Van Dam *et al.*, 1994). The laborious character of these measurements results in high costs. Cost-effectiveness can be improved by deriving hydraulic properties directly from basic soil properties such as texture and organic matter content. Methods developed for this purpose (e.g. Wösten and Van Genuchten, 1988; Vereecken *et al.*, 1989; Vereecken *et al.*, 1990) are referred to as 'pedotransfer' functions (Bouma and Van Lanen, 1986). Two basic types can be distinguished:

1. Class pedotransfer functions: soil horizons are grouped into taxonomic classes with associated average hydraulic properties (e.g. the Dutch 'Staring series'; Wösten, 1994);
2. Continuous pedotransfer functions: empirical regression functions relate hydraulic parameters to a sequence of basic soil properties including e.g. texture, soil organic matter (SOM) content and bulk density. Individual horizons are thus assigned specific hydraulic properties (as opposed to average hydraulic properties assigned through class pedotransfer functions).

Basic soil properties can be collected with relative ease. Pedotransfer functions therefore reduce the effort involved in soil sampling and laboratory analysis. This creates an opportunity to increase the sampling density, which is particularly relevant

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to soil variability studies. Reliability of pedotransfer estimates should however be scrutinised. Pedotransfer functions are based on general data sets and verification with 'true' field data is often lacking. Their general character can produce a high level of uncertainty (Finke *et al.*, 1996). Measurements may produce less uncertainty, but their limited number introduces considerable spatial uncertainty once point data are extrapolated to areas (e.g. soil units).

This study compares four methods to derive soil hydraulic properties by analysing their effect on simulated soil moisture contents. Applied methods include: (A) laboratory measurements, (B) class pedotransfer functions, (C) continuous pedotransfer functions and (D) continuous pedotransfer functions combined with simple laboratory measurements. Earlier studies conducted by Wösten *et al.* (1990 and 1995) did not include a 'combined' method. Specific objectives were therefore: (i) to evaluate the benefits of adapting a generic continuous pedotransfer function to local conditions by incorporating simple laboratory measurements and (ii) to formalise procedures in a systematical way allowing for application at other locations. Simulated soil moisture contents were compared with TDR field-measurements collected at three sites and two depths. Monte Carlo techniques were used to analyse modelling uncertainty and express the quality of derived hydraulic properties in probabilistic terms.

2.2 Materials and Methods

2.2.1 Study area

Research was conducted on a commercial arable farm in the central-western part of the Netherlands (51°17'N, 4°32'E). The farm covers an area of approximately 100 ha and applies a crop rotation with winter wheat, potato and sugar beet as the main cultivates. Soils originate from marine deposits and are generally calcareous with textures ranging from sandy loam to clay. They are characterised as Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50000 soil map (Vos, 1984). With excellent drainage conditions, the area is considered prime agricultural land.

2.2.2 Available soil data

During the spring of 1997 a detailed 1:5000 soil survey was conducted in the study area. Basic soil properties were collected for 612 geo-referenced soil-sampling sites and subsequently stored in a soil database. Texture and SOM-content were estimated directly in the field using hand texture and colour. Estimates were tested against a limited number of laboratory measurements to ensure accurate characterisation. Soil layers were grouped into relatively homogeneous classes defined by the Dutch 'Staring series' (Wösten *et al.*, 1994). This taxonomic classification distinguishes between topsoil and subsoil layers, which are further differentiated by textural composition and SOM-content. Sixteen classes were identified and sampled in the field (4 replicates).

Measured soil moisture contents were available for three sites located in different winter wheat fields. Measurements were collected during the 1997 growing season using TDR-devices installed at two depths (15 cm and 45 cm). Layer compositions of the corresponding soil profiles (sites 1-3) are presented in Fig. 2.1. Nine out of sixteen taxonomic layers from the 'Staring series' are represented in these profiles.

2.2.3 Generating soil hydraulic properties

Soil hydraulic properties were derived using four different methods:

A. Laboratory measurements: All identified taxonomic layers were sampled at two locations in the study area. Four replicate 300 cm^3 samples were collected for each layer and subsequently used to conduct multistep outflow measurements (Van Dam *et al.*, 1994). A pressure chamber system (Klute, 1986) provided additional moisture retention points at pressure heads (h) of -1000 cm and -16000 cm. Two larger samples (20 cm diameter and 20 cm height) were subjected to near-saturated conductivity measurements using the crust-infiltrometer method (Booltink *et al.*, 1991; $0 \leq h \leq -50$ cm). Hydraulic functions were derived through inverse optimisation using a computer program developed by Van Dam *et al.* (1994). Water retention and hydraulic conductivity curves were described by the Van Genuchten (Van Genuchten, 1980) and Gardner (Gardner, 1958) equations.

B. Class pedotransfer functions: Wösten *et al.* (1994) tabulated average soil hydraulic curves for all taxonomic layers in the 'Staring series'. These curves were derived from the 'Staring database'; a database containing physical measurements for 620 soil samples collected throughout the Netherlands. Water retention and hydraulic conductivity curves are described by the Mualem-Van Genuchten equations (Van Genuchten, 1980). As a set, the tabulated curves provide a unique source of soil physical information covering the entire spectrum of Dutch soils.

C. Continuous pedotransfer functions: Wösten (1997) developed a continuous pedotransfer function based on the same data set described under B. It consists of several regression functions relating hydraulic parameters for the Mualem-Van Genuchten equations (Van Genuchten, 1980) to basic soil properties such as texture, SOM-content and bulk density. Separate regression functions were established for sandy and loamy or clay horizons. Using the basic properties stored in the soil database a unique set of hydraulic parameters was derived for all layers shown in Fig. 2.1.

D. Continuous pedotransfer functions (C) combined with simple laboratory measurements (A): The generic continuous pedotransfer function described under C was adapted to local conditions using simple laboratory physical measurements. A sensitivity analysis performed by Vanclooster *et al.* (1992) identified saturated moisture content as the most sensitive parameter affecting water movement in a Typic Hapludalf (Soil Survey Staff, 1998). Similar results were reported by Diels

(1994). Based on this information the estimated saturated moisture contents derived under C were replaced with measured saturated moisture contents from A. Other hydraulic parameters remained unchanged.

2.2.4 Simulation model

Dynamic simulations of soil-water-plant interaction were conducted with the mechanistic-deterministic simulation model 'WAVE' (Water and Agrochemicals in soil and Vadose Environment) (Vanclooster *et al.*, 1994). WAVE integrates four existing models describing (i) one-dimensional soil water flow (SWATRER) (Dierckx *et al.*, 1986), (ii) heat and solute transport (LEACHN) (Hutson and Wagenet, 1992), (iii) nitrogen cycling (SOILN) (Bergström *et al.*, 1991) and (iv) crop growth (SUCROS) (Spitters *et al.*, 1988). Differential equations governing water movement and solute transport are solved with a finite difference calculation scheme. For this purpose soil profiles were divided into one-centimetre compartments. Water movement is described by the Richards' equation, which combines the mass balance and Darcian flow equations.

Water uptake by crops is calculated after Feddes *et al.* (1978). Maximum uptake rates are defined by a sink term (day^{-1}), which is considered constant with depth. Uptake is reduced at high and low pressure head values according to crop-specific thresholds. Verhagen (1997) made a conceptual change to the model. Instead of assuming preferential uptake in the upper soil compartments, water uptake is calculated as an integral over the entire root zone. Roots in deeper layers are therefore no longer excluded.

2.2.5 Monte Carlo simulations

A Monte Carlo approach was used to analyse modelling uncertainty in relation to the generated soil hydraulic functions. Monte Carlo techniques rely on the fact that the variability of input parameters can be described by probability density functions. Based on these functions, sampling techniques derive different combinations of selected parameters. Model output is generated for all combinations and input-output relations are scrutinised. The Monte Carlo approach is simple and can be applied to almost any simulation model.

Various sensitivity analyses of the WAVE model (Vanclooster *et al.*, 1992; Diels, 1994; Hoogervorst, 1999) indicated that a limited number of hydraulic parameters have a significant impact on water movement in soils. Vanclooster *et al.* (1992) found retention parameters to be more influential than conductivity parameters when simulating nitrate leaching from a Typic Hapludalf (Soil Survey Staff, 1998). They identified saturated moisture content ($cm^3\ cm^{-3}$) as most sensitive, followed by Van Genuchten shape parameter n (-) and α (cm^{-1}; inverse of the air-entry value). Residual moisture content ($cm^3\ cm^{-3}$) had no influence on model output. Diels (1994) found similar results with respect to water storage and drainage in a Haplaquod (Soil Survey

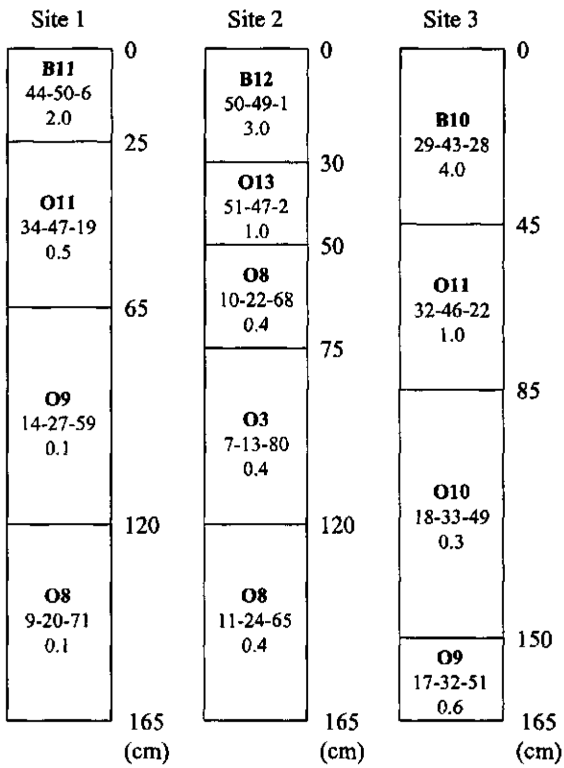

Fig. 2.1. Layer composition of the soil profiles at sites 1-3. Soil layers are coded according to their taxonomic class ('B' refers to topsoils, 'O' refers to subsoil layers), textural composition (percentages clay-silt-sand) and SOM-content (in percent).

Staff, 1998). The available information was used to select hydraulic parameters for the Monte Carlo simulations. A listing of selected parameters is presented in Table 2.1.

McKay *et al.* (1979) and Iman and Conover (1980) developed the concept of Latin Hyper Cube sampling. This technique stratifies the probability density function of p selected input parameters into N disjunct equiprobable intervals. One sample is collected from each interval resulting in N values per parameter. These values are randomly paired to generate N combinations of p parameters. Correlation among parameters is taken into account. The adequate number of combinations varies between $2p$ and $5p$, which is much lower than the number required for random sampling ($N > 10p$; Janssen *et al.*, 1993).

Probability density functions for selected input parameters were either derived from replicate measurements (method A) or based on information from the 'Staring series' (method B) and the soil database (method C). In total 99 distributions were

Table 2.1. Soil hydraulic parameters included in the Monte Carlo simulations. Moisture retention curves are described by the Van Genuchten closed form equation (Van Genuchten, 1980). Hydraulic conductivity curves are either described by the Gardner equation (Gardner, 1958; method A) or by the Mualem-Van Genuchten equation (Van Genuchten, 1980; methods B, C and D). Method D uses measured saturated moisture contents.

Parameter	Distribution	Description
A. Laboratory measurements		
- smc	normal	saturated moisture content
- rmc	fixed	residual moisture content
- *n*	normal	van Genuchten shape parameter
- alpha	fixed	inverse of air entry value
- K_{sat}	fixed	Saturated hydraulic conductivity
- beta	fixed	Gardner shape parameter
- lambda	normal	Gardner shape parameter
B. Class pedotransfer function		
- smc	uniform	saturated moisture content
- rmc	fixed	residual moisture content
- *n*	fixed	van Genuchten shape parameter
- alpha	fixed	inverse of air entry value
- K_{sat}	uniform	Saturated hydraulic conductivity
- gamma	fixed	van Genuchten shape parameter
C. Continuous pedotransfer function		
- smc	Normal	saturated moisture content
- rmc	Fixed	residual moisture content
- *n*	Normal	van Genuchten shape parameter
- alpha	Fixed	inverse of air entry value
- K_{sat}	Normal	Saturated hydraulic conductivity
- gamma	Fixed	van Genuchten shape parameter
D. Continuous pedotransfer function combined with laboratory measurements		
- smc	Normal	saturated moisture content
- rmc	Fixed	residual moisture content
- *n*	Normal	van Genuchten shape parameter
- alpha	Fixed	inverse of air entry value
- K_{sat}	normal	saturated hydraulic conductivity
- gamma	fixed	van Genuchten shape parameter

specified for 11 parameters (Table 2.1) and 9 taxonomic soil layers (Fig. 2.1). Due to the limited number of measurements, no probability density functions could be specified for saturated hydraulic conductivity in method A. Using results from the inverse parameter optimisation (*i.e.* 95% confidence intervals were provided for all optimised parameters) distributions could be specified for Gardners' shape parameters beta and lambda. Since beta and lambda showed strong correlation, only lambda was included in the sampling procedure. With respect to method B, detailed information regarding parameter distributions was lacking. Uniform distributions were assumed for saturated moisture content and hydraulic conductivity. Minimum and maximum values were derived from the 'Staring series'. No distributions could be specified for Van Genuchtens' shape parameter *n*. Parameter distributions for method C were determined by analysing the parameter set as it was derived from the basic soil properties in the soil database. Since Van Genuchtens' parameters *n* and alpha showed strong correlation, only *n* was included in the Monte Carlo sampling. Finally, distributions for method D were derived by combining parameter distributions from methods A and C.

Different sets of model input were sampled for methods A-D (4*p* combinations) and sites 1-3 (12 sets in total). Simulations were conducted for all input combinations using meteorological data collected in the study area during 1997. Potential evapotranspiration was calculated by multiplying the Makkink reference evapotranspiration (Makkink, 1957) with a series of crop specific factors tabulated by Feddes (1987). Water uptake was calculated over a root zone of 90cm, corresponding to the average rooting depth of winter wheat (Van Noordwijk and Brouwer, 1991). Model output consisted of soil moisture contents calculated for two depths. Simulation depths were chosen in correspondence with the installation depths of the TDR-sensors.

2.2.6 Evaluation of modelling performance and modelling uncertainty

Modelling performance was evaluated by comparing measured and simulated soil moisture contents. Two statistical measures were derived for each of the generated hydraulic functions and for the individual sites and depths. They are defined as:

Mean residual error (*ME*):

$$ME = (1/n)\sum_{i=1}^{n}(p_i - o_i)$$

Root mean squared residual error (*RMSE*):

$$RMSE = \sqrt{(1/n)\sum_{i=1}^{n}(p_i - o_i)^2}$$

where p_i are predicted soil moisture contents, o_i are observed soil moisture contents and n is the number of observations. *ME* is a measure of the bias in the simulated results. Values close to zero indicate that measured and simulated moisture contents do not differ systematically from each other or, equivalently, that there is no consistent bias. *RMSE* is a measure for the scatter around the 1:1 linear relation between measured and simulated data points. Low values indicate little scatter.

Linear regression was used to scrutinise relations over the entire data set (*i.e.* measured and simulated data for the 3 sites and 2 depths). Regression functions and corresponding coefficients of determination (r^2, where r is the correlation coefficient) were calculated for each of the generated hydraulic functions.

Modelling uncertainty was derived from the results of the Monte Carlo simulations. The half width of the 95% confidence interval for simulated soil moisture contents (equal to twice the standard deviation) was selected as a measure of uncertainty. Half widths were calculated for each set of input parameters (methods A-D and sites 1-3) and for days on which TDR-measurements were collected.

2.3 Results and Discussion

Statistical measures derived from the differences between measured and simulated soil moisture contents are summarised in Table 2.2. Considering the entire data set (3 sites - 2 depths) *ME* and *RMSE* values were clearly smallest for method D. The combination of continuous pedotransfer functions and simple laboratory measurements resulted in unbiased (*ME* = -0.001 cm^3 cm^{-3}) and accurate (*RMSE* = 0.024 cm^3 cm^{-3}) simulations. Other methods showed a tendency to over-estimate ($0.016 \leq ME \leq 0.029$ cm^3 cm^{-3}) and were less accurate overall ($0.035 \leq RMSE \leq 0.073$ cm^3 cm^{-3}). Results for individual soil profiles and depths confirmed the consistent accuracy of method D. Only for site 2 - depth 15cm did measured data (method A) provide slightly better results. The difference, however, was minimal.

Figure 2.2 presents regression lines for the different hydraulic functions. Slopes varied between 0.303 (method B) and 0.986 (method D) with corresponding intercepts of 0.255 and 0.006 cm^3 cm^{-3}. The 1:1 relation was best approached by method D, other methods deferred (strongly) from this ideal case. Coefficients of determination showed a similar pattern: the maximum value was reached for method D ($r^2 = 0.658$) while other methods rendered substantially lower values ($0.396 \leq r^2 \leq 0.465$).
Modelling uncertainty varied between methods and within the simulation period. Figure 2.3 presents simulated and measured soil moisture contents for site 2 - depth 15 cm. Uncertainty measures are included for days on which TDR measurements were collected. Methods B and C clearly overestimated soil moisture contents, which is reflected in high values of *ME* (0.084 and 0.078 cm^3 cm^{-3}) and *RMSE* (0.088 and 0.084 cm^3 cm^{-3}). Methods A and D provided more accurate results with *ME* values close to zero (*i.e.* no bias) and *RMSE* values of 0.030 and 0.034 cm^3 cm^{-3}. The half width of the 95% confidence interval for simulated moisture contents was by far the largest for method A (0.213 cm^3 cm^{-3} on average over the simulation period). Half widths were much narrower for methods C and D (averages of 0.019 and 0.018 cm^3 cm^{-3}). This implies that modelling uncertainty under A is not caused by the variability of measured saturated moisture contents. These were used in method D (*i.e.* a combination of A and C) without increasing modelling uncertainty compared to method C.

When considering the entire data set modelling uncertainty turned out the largest for method A. This was not surprising since laboratory measurements are conducted with a limited number of replicates. Averaged over the simulation period the half

Table 2.2. Mean error (ME) and root mean square error (RMSE) resulting from differences between measured and simulated soil moisture contents. Values are presented for four hydraulic functions (methods A-D), three sites and two depths. 'Soil Profile' contains the combined result over 15 and 45 cm.

	Depth 15cm		Depth 45cm		Soil Profile	
Method	*ME*	*RMSE*	*ME*	*RMSE*	*ME*	*RMSE*
	$cm^3\ cm^{-3}$					
Site 1						
A. measurements	0.021	0.044	0.019	0.028	0.020	0.037
B. class-ptf	0.118	0.121	-0.031	0.033	0.043	0.089
C. continuous-ptf	0.035	0.047	-0.005	0.017	0.015	0.035
D. combination	0.001	0.033	0.002	0.015	0.001	0.026
Site 2						
A. measurements	0.001	0.030	0.001	0.016	0.001	0.024
B. class-ptf	0.084	0.088	0.055	0.058	0.072	0.076
C. continuous-ptf	0.078	0.084	-0.012	0.016	0.035	0.062
D. combination	-0.002	0.034	-0.005	0.012	-0.004	0.026
Site 3						
A. measurements	0.040	0.051	0.016	0.034	0.028	0.043
B. class-ptf	-0.039	0.050	-0.037	0.040	-0.038	0.045
C. continuous-ptf	0.009	0.020	-0.016	0.026	-0.004	0.023
D. combination	-0.008	0.020	0.005	0.019	-0.001	0.019
Sites 1,2 and 3						
A. measurements	0.010	0.030	0.006	0.019	0.016	0.035
B. class-ptf	0.030	0.066	-0.001	0.032	0.029	0.073
C. continuous-ptf	0.021	0.041	-0.005	0.014	0.016	0.044
D. combination	-0.001	0.021	0.000	0.011	-0.001	0.024

width of the 95% confidence interval for simulated moisture contents equalled 0.097 $cm^3\ cm^{-3}$. Uncertainty was smallest for method D (half width = 0.053 $cm^3\ cm^{-3}$), followed by methods C and B (half widths of 0.057 and 0.084 $cm^3\ cm^{-3}$). Note that incorporation of measured saturated moisture contents in method D slightly lowered modelling uncertainty compared to method C. This again confirmed that modelling uncertainty under A is not caused by the variability of measured saturated moisture contents.

Summarising, the combination of continuous pedotransfer functions and simple laboratory measurements (method D) produced best results. Modelling performance was highest overall and results were consistent for individual profiles and depths. Modelling uncertainty was lowest, even slightly lower than results obtained with the continuous pedotransfer function solely. The class pedotransfer function (method B) performed poorly, both in terms of modelling performance and modelling uncertainty. Results obtained through measurements (method A) and the continuous pedotransfer

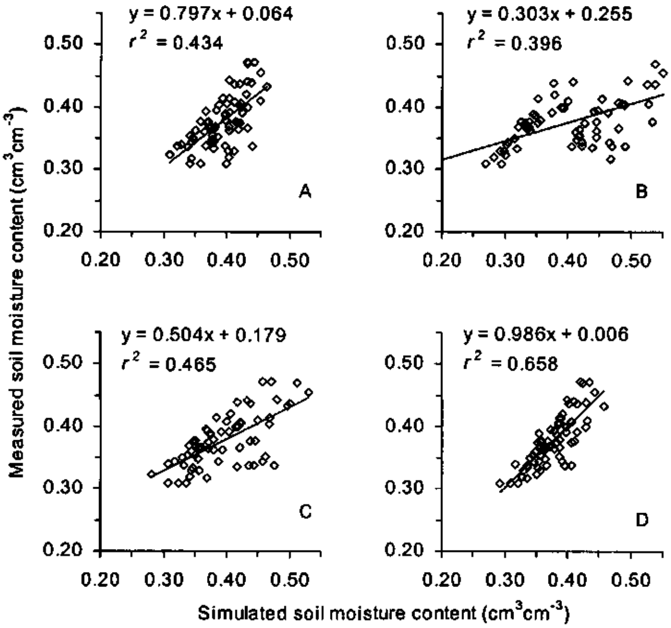

Fig. 2.2. Regression equations and coefficients of determination (r^2) describing the relation between measured and simulated soil moisture contents for methods A-D.

function (method C) varied between sites. Measurements performed slightly better overall, caused by poor results for the continuous pedotransfer function at site 2. Modelling uncertainty was larger for the measured data.

The fact that the combined method performed best implies that the continuous pedotransfer function quite accurately described soil moisture variations. In absolute terms, however, simulations were badly 'positioned' due to inaccurate estimates of the saturated moisture content. This is clearly illustrated by Fig. 2.3: trends are comparable for methods C and D, but positioning is far better for the latter.

Presented results need to be verified for other regions and soil types. If this can be done successfully, the developed procedure will offer an opportunity to reduce the (sampling) costs involved in deriving soil hydraulic properties. In turn, this would enhance the possibility to include simulation modelling in large-scale, data-intensive field variability studies. The proposed procedure consists of the following steps:

1. Perform a sensitivity analysis for the selected model to determine its relative sensitivity to different hydraulic parameters. Results from earlier studies can be used if available.
2. Collect measurements for the most sensitive parameter that can be measured accurately and with relative ease.

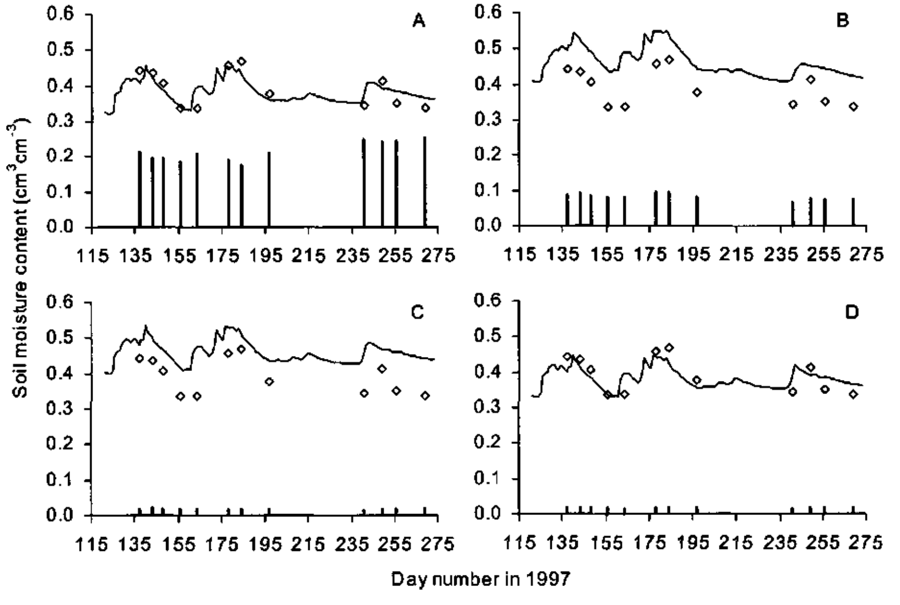

Fig. 2.3. Measured (◊) and simulated (—) soil moisture contents for site 2 - depth 15cm. Simulations were based on four different hydraulic functions (methods A-D). Modelling uncertainty is reflected by half widths of the 95% confidence interval for simulated soil moisture contents (|). Half widths were derived from the Monte Carlo simulations.

3. Combine these measurements with estimates of less sensitive parameters. Estimates can be derived through continuous pedotransfer functions.
4. Evaluate modelling performance by comparing measured and simulated data. Modelling uncertainty can be analysed through Monte Carlo simulations (including correlation among parameters).

2.4 Conclusions

1. Combining continuous pedotransfer functions with simple laboratory physical measurements increased modelling performance. Simulation results obtained through pedotransfer functions or measurements only were clearly less accurate. Results were consistent for individual soil profiles and depths.
2. Modelling uncertainty was lowest for the combined method, far lower than the uncertainty resulting from measured data. This indicates that: (i) the general character of pedotransfer functions produced less uncertainty than the limited number of replicate measurements and (ii) high uncertainty associated with measurements was not caused by the variability of measured saturated moisture contents (these were incorporated in the combined method).

3. The proposed procedure offers an opportunity to combine the cost-effectiveness of pedotransfer functions with the accuracy of laboratory measurements. Uncertainty associated with measurements is restricted by focusing on the collection of a few sensitive parameters that can be measured accurately and with relative ease. Sampling density can hereby be increased without creating extra costs.

CHAPTER 3

A Functional Approach to Soil Characterisation in Support of Precision Agriculture[2]

3.1 Introduction

The tightening of economical and environmental constraints on agriculture has resulted in a call for more efficient management systems. Besides maximizing crop production, the input of fertilisers and biocides should be reduced to a minimum. Precision agriculture (PA) responds to this challenge by developing management strategies that incorporate field variability. Soil information is crucial here, as soils are a major source of variation.

Soil databases have been assembled in many countries to provide easy access to soil information. Some examples are the State Soil Geographic (STATSGO; National Resources Conservation Service, 1995a) and Soil Survey Geographic (SSURGO; National Resources Conservation Service, 1995b) databases in the USA and the National Soil Survey database of the Netherlands (Bregt *et al.*, 1987). While readily available, the application of these databases in PA has proven cumbersome. Stermitz *et al.* (1999) found SSURGO data to be of little value in explaining yield variations. In more general terms the National Research Council (1997) concluded that: "current soil surveys satisfy few of the data requirements for PA. Soil data are not at the appropriate level of detail, nor are the indexes required by PA the same as those provided by soil surveys." This was not surprising since soil survey data were never intended for use in PA. Their conclusion does, however, raise three important questions:

1. Which requirements does PA pose on soil information?
2. How can the desired information be produced?
3. How can soil information be 'translated' into recommendations for precision management?

An interdisciplinary research team in the Netherlands is currently seeking answers to these questions. Although research is still in progress, the outline of a decision support system (DSS) for PA is taking shape. The system, which is designed for arable farming and reflects Dutch conditions, was described in detail by Bouma *et al.* (2000).

The DSS is founded on a detailed soil database constructed specifically for PA. Bouma *et al.* (2000) state that a similar database will be required for most farms switching to precision management, as it provides the only means to reach an adequate level of detail. The soil database contains both primary (*e.g.*, texture, organic

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matter content) and secondary soil data (*e.g.*, hydraulic parameters) for a large number of soil auger observations. Secondary data are derived through continuous pedotransfer functions (Wösten *et al.*, 1998).

Sampled soil profiles are characterised in terms of their water regimes and nutrient dynamics under varying weather conditions. This is referred to as 'functional' characterisation, as opposed to traditional 'taxonomic' characterisation (*e.g.*, Soil Taxonomy) (Soil Survey Staff, 1998). Soil functional properties are derived using a mechanistic-deterministic simulation model, which forms the core of the DSS. Based on functional similarity, the soil profiles are grouped into functional classes. This information is subsequently interpolated to identify soil functional units at the field level. These units serve as management units for PA (Van Uffelen *et al.*, 1997).

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

This paper describes the development of two important DSS components: (i) construction of a soil database at the farm level and (ii) delineation of soil functional units at the field level. Soil information relevant to PA is identified and methods for producing this information are presented (*i.e.*, questions 1 and 2 formulated above). Anticipated applications for soil information in operational decision support (*i.e.*, question 3) are closely considered and receive special attention in the results and discussion section.

3.2 Materials and Methods

3.2.1 Study Area

Research was conducted on a commercial arable farm in the central-western part of the Netherlands (51°17'N, 4°32'E). The farm covers an area of approximately 100 ha and applies a crop rotation of winter wheat, consumption potato and sugar beet. Two fields were included in the study, covering areas of 14.7ha (field A) and 10.5ha (field B). Soils originate from marine deposits and are generally calcareous with textures ranging from sandy loam to clay. They are characterised as Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50,000 soil map (Vos, 1984). Soil variability is large and expressed through differences in texture (average clay content over 0-100cm varies from 14% to 50%), soil organic matter (SOM) content (average SOM content over 0-100cm varies from 0.5% to 5.8%) and subsoil composition (peat or mineral matter). With excellent drainage conditions, the area is considered prime agricultural land.

3.2.2 Soil Database

A detailed 1:5,000 soil survey was conducted in the study area, counting approximately 6 soil auger observations per hectare. Results were stored in a soil database containing soil physical and soil chemical properties for individual soil layers. Texture and SOM-content were estimated directly in the field and tested against a limited number of laboratory measurements to ensure accurate characterisation. Based on these properties, soil layers were grouped into relatively homogeneous classes as defined by the 'Staringreeks' (Wösten *et al.*, 1994). This classification distinguishes between topsoil and subsoil layers, which are further differentiated by textural composition and SOM-content. Sixteen classes were identified and sampled in the field. Average bulk density and saturated moisture content were determined for each class using at least 4 replicate samples.

Soil hydraulic characteristics were derived through a continuous pedotransfer function (PTF) developed at the DLO-Staring Center (Wösten *et al.*, 1998). The PTF is based on soil physical measurements for 620 soil samples collected from major soil types in the Netherlands. It relates basic soil properties such as texture, SOM-content and bulk density to a set of Van Genuchten parameters (Van Genuchten, 1980) describing the moisture retention and hydraulic conductivity curves for individual soil layers. A sensitivity analysis by Vanclooster *et al.* (1992) identified the saturated moisture content as the most sensitive parameter affecting nitrate leaching from a Typic Hapludalf (Soil Survey Staff, 1998). Considering their results, measured saturated moisture contents were used to replace the PTF-estimates.

Based on the layer information, soil profiles were classified according to the standards of the Dutch 1:50,000 national soil map (Bregt *et al.*, 1987). This classification focuses on genetic origin, topsoil texture, profile structure and lime content. Following from its traditional design, the classification was chosen as a reference for the proposed functional classification.

Monitoring sites were installed at strategic locations in each field of the farm to provide a validation set for the simulation model. Groundwater levels and soil moisture contents were measured weekly during 1997. Moisture contents were measured at two depths (approximately 15cm and 45cm) using time domain reflectometry (TDR). As a result of their laborious character, soil-N measurements were concentrated on a single winter wheat field. Throughout 1998, monthly samples were collected at 10 sites and two depths (0-30cm and 30-100cm). Nitrate-N, ammonia-N and total-N concentrations were measured in a 50 ml KCl (1 *M*) soil extract using the Technicon-Auto-Analyzer II.

Table 3.2. Summary of precipitation (P) and potential evapotranspiration (ET_{pot}) for a wet year (1987) and a dry year (1989).

	January – December		March - August	
Year	P	Et_{pot}	P	Et_{pot}
	mm			
1987	766	565	452	457
1989	526	651	230	526

3.2.5 Fuzzy Classification

Fuzzy c-means classification (FCM) was applied to identify classes of functionally similar soil profiles. Several authors, *e.g.*, Burrough (1996) and McBratney and Odeh (1997), have described FCM classification. As opposed to traditional discrete classifiers, FCM expresses class-membership on a continuous scale of zero to one. Observations are assigned a specific membership vector containing partial membership values for each designated class. The sum of these membership values is by definition equal to one (*i.e.*, constant sum constraint). The concept of partial class-membership provides additional interpretative information that would not be available if a discrete classifier were used. FCM also enables the derivation of validity measures to assist in the selection of an appropriate number of classes and, finally, membership values can be interpolated with standard techniques to provide for continuously varying soil maps.

FCM classification was performed on the four functional properties derived in the simulation runs (*i.e.*, water stress, N-stress, N-leaching and residual N-content). Scaling and mutual correlation were accounted for by calculating the Mahalanobis distance between observations. The FUZNLM program (Vriend and Van Gaans, 1984), based on an FCM algorithm by Bezdek *et al.* (1984), derived multiple classifications for the two fields included in this study. In both fields the number of functional classes varied between 2 and 7. Two validity measures were derived for each classification: the fuzziness performance index (F') and the normalised classification entropy (H'') (Roubens, 1982). These measures quantify a degree of 'non-fuzziness', which is maximised when F' and H'' reach their minimum value. McBratney and Moore (1985) indicate that the corresponding number of classes reflects a balance between structure and continuity that is generally pursued. The appropriate number of classes is thus derived from the data set, thereby eliminating a source of subjectivity from the classification.

3.2.6 Interpolation and Boundary Detection

Class-membership values for all soil profiles were interpolated using ordinary kriging (Journel and Huybregts, 1978). This required separate interpolations for each

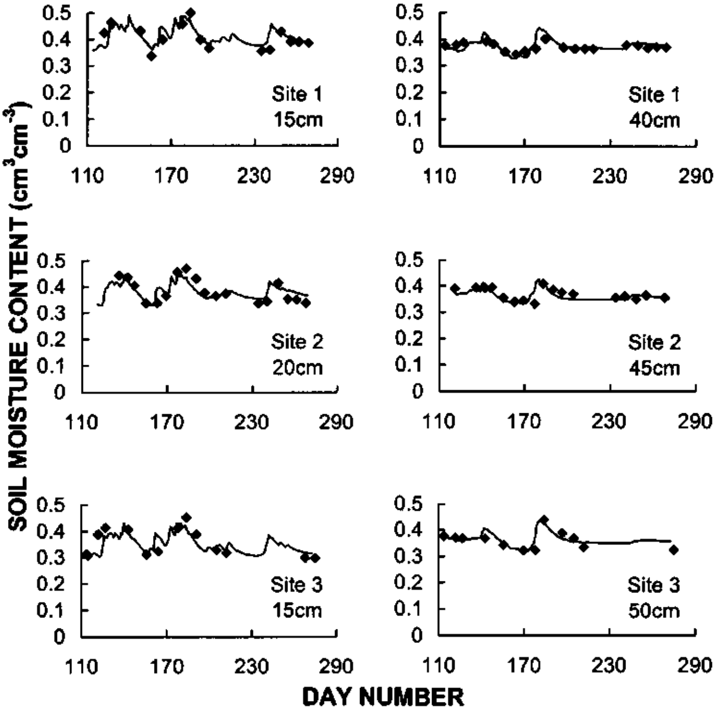

Fig. 3.1. Measured (♦) and simulated (—) soil moisture contents. Measurements were collected from three winter wheat fields (sites 1-3) during the 1997 growing season.

functional class resulting in multiple grid maps. These grids were combined to derive a single confusion index map (*CI*-map) for both fields. The *CI* is defined as (Burrough *et al.*, 1997):

$$CI = 1 - (\mu_{1,i} - \mu_{2,i})$$

in which $\mu_{1,i}$ is the highest membership value in grid cell i and $\mu_{2,i}$ is the second largest membership value in the same grid cell. In cases where *CI*-values approach 0, one functional class clearly dominates leaving little confusion about class membership. Where *CI*-values approach 1, two classes have similar membership values resulting in 'confusion' about class membership. On the *CI*-map these areas indicate 'transition zones' between the functional classes. A boundary detection algorithm (ESRI, 1998) placed boundaries along these zones to delineate soil functional units. Each unit was assigned a representative soil profile that best matched the functional characteristics of its class (*i.e.*, a selection of the highest membership value).

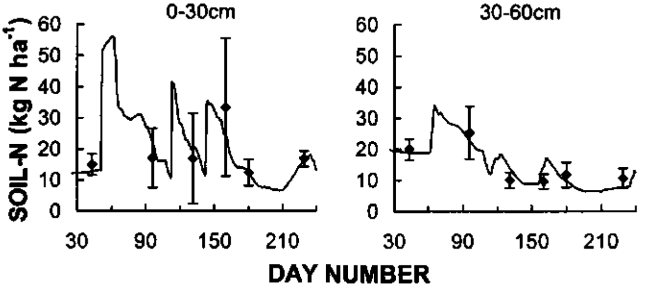

Fig. 3.2. Measured (♦) and simulated (—) soil N contents. Measurements were collected from a winter wheat field during the 1998 growing season.

3.2.7 Analysis of Variance

Coefficients of determination were calculated to verify the efficiency of the fuzzy classification procedure. The coefficient of determination (R^2 in percent) is defined as (Devore and Peck, 1986):

$$R^2 = \left(1 - \frac{SSW}{SST}\right) * 100\%$$

in which R^2 is calculated as a function of SSW, the sum of squares within strata, and SST, the total sum of squares. Available soil functional and soil physical properties were stratified according to the class-membership of the corresponding soil profiles. R^2 values were calculated for each property, indicating the percentage of the total spatial variation explained by the functional classes. This was interpreted as an efficiency indicator. A second series of R^2 values was derived using traditional soil classes for stratification. This series served as a reference for the functional classification.

3.3 Results and Discussion

3.3.1 Model Validation

Model performance was tested against measurements available in the soil database. Figure 3.1 presents simulated and measured (1997) soil moisture contents for three sites located in separate fields. The overall coefficient of determination is 66%. Figure 3.2 presents simulated and measured (1998) soil nitrogen concentrations. Each

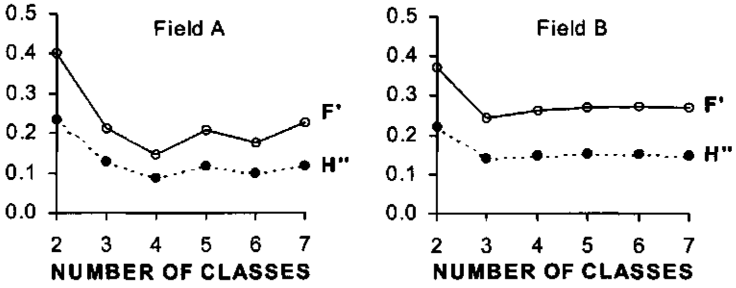

Fig. 3.3. Validity measures calculated for the FCM classifications in fields A and B.

measurement represents an average concentration based on 10 samples taken from a single field. Steep increases of nitrogen concentrations were induced by split fertiliser applications on days 52, 113 and 140. The overall coefficient of determination equals 71%.

3.3.2 Soil Functional Classification

Figure 3.3 presents validity measures derived for the different FCM classifications in fields A and B. In both cases F' and H'' clearly identified an appropriate number of classes. Their values decreased to a minimum before continuing to increase slightly with the number of classes. Minimizing both measures resulted in 4 soil functional classes in field A and 3 soil functional classes in field B.

Tables 3.3 and 3.4 present soil functional and soil physical properties for the designated classes. Nitrogen stress never occurred in either field, causing actual and potential N-uptake to coincide ($\frac{N_{act}}{N_{pot}} = 1$). This was not surprising since management parameters reflected common practice with abundant N-fertilisation. Water stress did occur and is represented by low values of $\frac{ET_{act}}{ET_{pot}}$. In both fields the sensitivity to water stress was highest for class 2. The corresponding soil profiles appeared to contain a heavy non-calcareous subsoil layer hindering the upward flux of groundwater during summer. The presence of this layer is reflected in the relatively high clay content over 0-100cm.

Table 3.3. Soil functional and soil physical properties (± SD) for the functional classes in field A. Count indicates the number of soil profiles grouped in each class; R^2 indicates the percentage of spatial variation explained by functional (Func.) and traditional 'taxonomic' classes (Tax.).

Class	Count	Water stress	N-stress	N-leaching	N-residual	Clay 0-100cm	SOM 0-100cm
				kg N ha^{-1}		%	
1	25	0.99 (0.02)	1.00 (0.00)	29.8 (4.1)	90.1 (14.3)	41.8 (4.5)	0.9 (0.2)
2	16	0.71 (0.07)	1.00 (0.00)	37.1 (6.9)	106.3 (19.3)	46.3 (3.0)	1.8 (0.3)
3	30	0.98 (0.04)	1.00 (0.00)	36.8 (3.3)	86.9 (10.9)	30.7 (7.6)	1.2 (0.3)
4	10	0.96 (0.06)	1.00 (0.00)	56.3 (9.1)	154.5 (16.5)	33.7 (7.4)	3.1 (1.1)
R^2(%)	Func.	86	100	71	70	56	70
	Tax.	13	100	41	32	53	17

Table 3.4. Soil functional and soil physical properties (± SD) for the functional classes in field B. Count indicates the number of soil profiles grouped in each class; R^2 values indicate the percentage of spatial variation explained by the functional (Func.) and the traditional 'taxonomic' classes (Tax.).

Class	Count	Water stress	N-stress	N-leaching	N-residual	Clay 0-100cm	SOM 0-100cm
				kg N ha^{-1}		%	
1	31	1.00 (0.01)	1.00 (0.00)	24.4 (2.8)	85.1 (8.0)	26.8 (7.5)	1.4 (0.4)
2	5	0.77 (0.05)	1.00 (0.00)	24.9 (2.9)	94.8 (3.5)	40.8 (4.5)	2.1 (0.1)
3	22	0.98 (0.04)	1.00 (0.00)	33.3 (3.8)	117.5 (10.9)	23.3 (6.6)	3.1 (0.5)
R^2(%)	Func.	83	100	65	75	32	76
	Tax.	36	100	14	9	88	11

A greater variation of N-leaching and residual-N contents explained the larger number of classes in field A (4 versus 3 in field B). SOM-content appeared to play a dominant role through the effects of N-mineralisation. Due to the abundant fertilisation, mineralised-N was not entirely used for crop production and, as a consequence, contributed to N-leaching and/or residual-N contents. Water regimes strongly influence this effect, as can be illustrated for field A. Nitrogen leaching is practically identical for classes 2 and 3, even though class 2 contains 50% more SOM. This implies that soils in class 3 leach their N-residues at a greater pace. Most likely, this is a consequence of their lighter texture (less clay), which reduces water retention capacity and increases hydraulic conductivity. Compared to class 3, class 1 combines a higher residual-N content with 25% less SOM. In this case a heavier texture increases water retention and reduces hydraulic conductivity; the residence time for residual-N therefore increases.

Analysis of variance revealed the efficiency of the functional classification: coefficients of determination exceeded 65% for all functional properties (Tables 3.3 and 3.4). Traditional 'taxonomic' classification rendered substantially lower values. The same result was found for SOM-content: functional classes explained over 70% of the spatial variation compared to only 17% (field A) and 11% (field B) for the taxonomic classification. This was not surprising since the taxonomic classes did not discriminate within the SOM-range encountered in the study area (0.5%-5.8%). Clay content showed a somewhat different picture: while functional classes rendered a slightly higher R^2 value in field A, taxonomic classes could better describe the textural differences in field B. This illustrates the flexibility of functional characterisation; textural differences are only described as far as they have an effect on functional characteristics. Another striking difference between both classifications concerns the number of classes. Taxonomic classification rendered more classes in both fields: 7 versus 4 in field A and 8 versus 3 in field B. This confirmed the efficiency of the functional classification.

3.3.3 Delineating Soil Functional Units

Figures 3.4 and 3.5 present grid maps describing the spatial distribution of class-membership values across fields A and B. Semivariogram parameters used for interpolation are included in Table 3.5. Transition zones between functional classes, appearing as light coloured areas on the *CI*-map, formed clear patterns in both fields. Based on this confirmation of spatial grouping, soil functional units were delineated using $CI > 0.9$ as a threshold level for boundary detection. The delineated units are included in Figures 3.4 and 3.5, along with their representative soil profiles.

Table 3.5. Spherical variogram models fitted to the membership values of the soil functional classes in fields A and B. Goodness of fit was determined by the ratio SS_D/SS_T [0,1]; perfect fit is attained when this ratio equals zero.

Field	Class	SS_D/SS_T	Nugget	Scale	Range
					m
A	1	0.034	0.029	0.146	85.0
	2	0.013	0.000	0.085	63.2
	3	0.085	0.049	0.170	294.0
	4	0.125	0.000	0.038	100.0
B	1	0.049	0.000	0.191	81.5
	2	0.057	0.000	0.105	91.9
	3	0.142	0.000	0.165	72.9

3.3.4 *Application in Precision Farming*

Within the DSS, soil functional units serve as a tool to reduce the theoretically infinite variability of soils to a limited, functional set that can be analysed with simulation models. This is considered important since real-time simulations provide estimates of the actual supply and demand for water and N. A fertilisation experiment conducted in 1998 confirmed the relevance of these data (Van Alphen and Stoorvogel, 2001[a]). Figure 3.6 presents simulated soil-N concentrations and weekly N-uptake rates

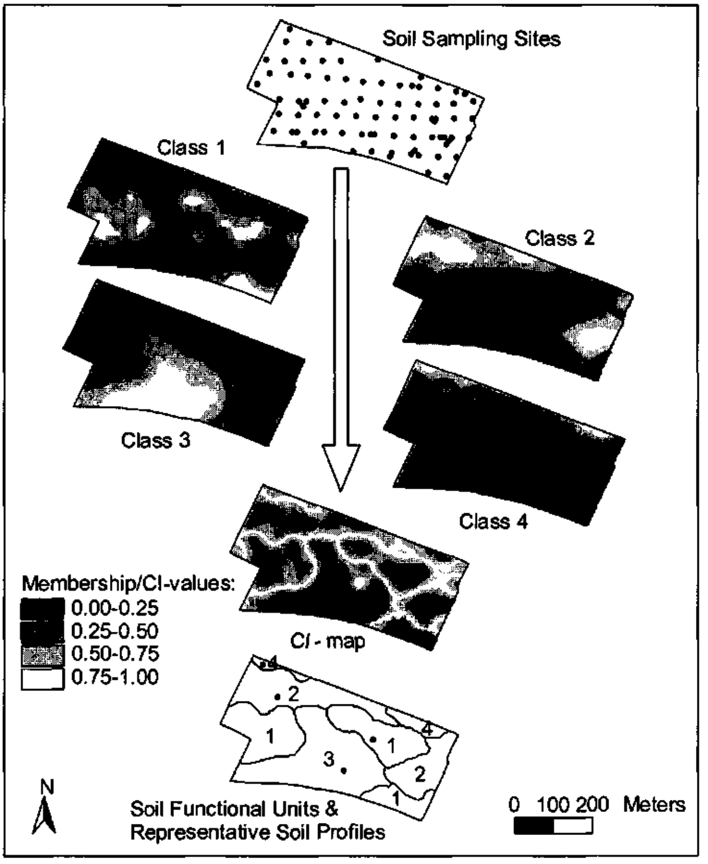

Fig. 3.4. Soil sampling sites in field A; spatial distribution of class-membership values; *CI*-map reflecting spatial uncertainty of class-membership; soil functional units with representative soil profiles.

for a soil functional unit in the experimental winter wheat field. After a standard base-fertilisation on day 52, this unit received two additional N-fertilisations in reaction to early warning signals from the DSS (days 113 and 140). Early warning signals were generated once simulated soil-N concentrations dropped below a critical threshold level, which was defined in accordance with the actual N-uptake rate. This strategy for 'precise' fertilisation was compared to conventional management in the same field. Precision management proved efficient in reducing fertiliser inputs (-23%), while slightly improving grain yields (+3%) and hectolitre weights (+4%). A similar experiment is being conducted in the study area to verify these results under different conditions.

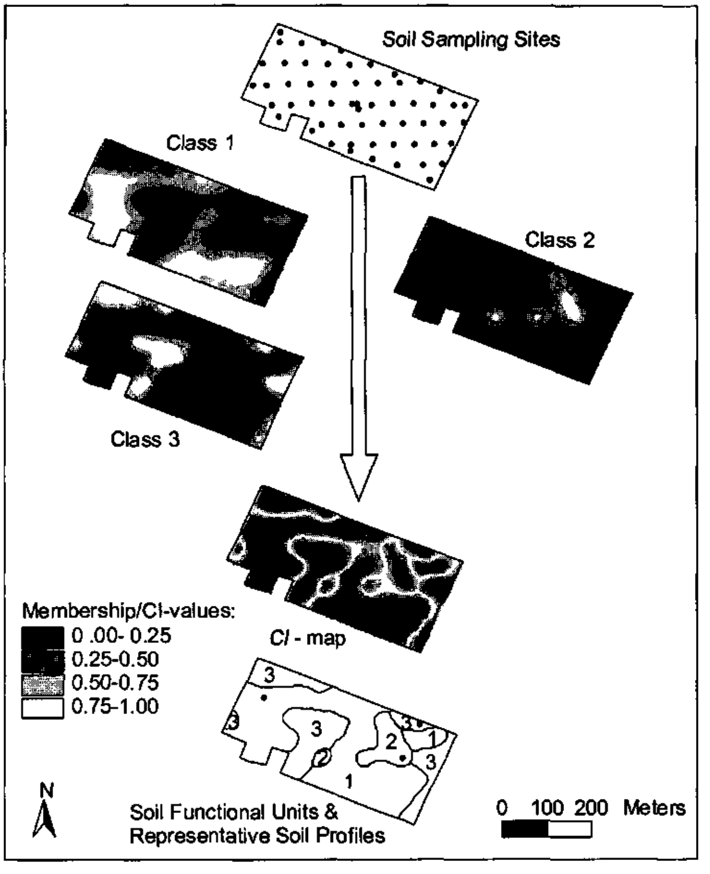

Fig. 3.5. Soil sampling sites in field B; spatial distribution of class-membership values; *CI*-map reflecting spatial uncertainty of class-membership; soil functional units with representative soil profiles.

While the implicit aim of PA is to treat each site according to its individual requirements, the enormous expense of data collection for informed decisions at this scale currently preclude the adoption of such intensive management programs (Whelan, 1999). Instead, various forms of spatial generalisation have been proposed to derive management units for PA (*e.g.*, Boydell and McBratney, 1999; Blackmore and Larscheid, 1997; Lark and Stafford, 1997; Van Uffelen *et al.*, 1997). Based on the results of this study, it may be argued whether near-continuous variation of management operations should be pursued in all cases. Soil functional units derived in the study area could well describe the spatial variation of selected soil functional properties. Coefficients of determination exceeded 65% in all cases, meaning that less than 35% of the total variation was lost through generalisation. If similar results can

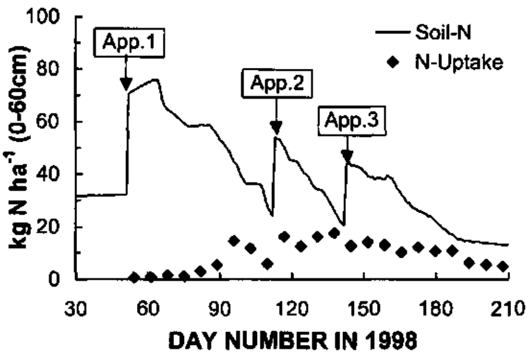

Fig. 3.6. Simulated soil-N concentrations and weekly N-uptake rates used to optimize N-fertilisation in a soil functional unit during 1998.

be shown for other regions, it will remain doubtful whether continuous adaptive management will become cost efficient and, if so, for which farming systems and management operations this will be the case.

Proposed methods for delineating management units often combine spatial and temporal analysis of yield data to identify areas showing a characteristic behaviour over multiple years. Yield data are either measured on a combine harvester (Lark and Stafford, 1997), calculated with simulation models (Van Uffelen et. al, 1997) or estimated from remote sensing images (Boydell and McBratney, 1999). Once management units have been established, important soil properties can be sampled in the field to identify the cause(s) of yield variations and enable site specific treatment. Management units are thus used to stratify fields in order to increase sampling efficiency (*e.g.*, variable N-fertilisation based on N-sampling in early spring). Methods applied in the DSS add some advantages to this general concept. Yield patterns originate from the integrated effects of physical, chemical and biological factors on crop production. Therefore they are difficult to interpret without additional soil information. Soil functional units, on the other hand, are well defined in terms of their soil functional characteristics. These may not reflect all sources of variation (*e.g.*, the influence of pests and diseases is excluded), but they clearly describe the varying availability of major growth-determining factors (*i.e.*, water and nitrogen). In addition, real time simulations for representative soil profiles offer the opportunity to implement a pro-active management strategy. Early warning signals generated by the DSS enable a farmer to respond before the crop is affected by stress. In this way the timing of management operations can be optimised, which has been shown a crucial factor in high-input farming systems in the Netherlands (Van Alphen and Stoorvogel, 2001[a]). These systems are characterised by multiple treatments throughout the growing season (*e.g.*, up to 4 split N-fertilisations in winter wheat) and are subjected to strict environmental regulations. The DSS, with soil functional units as its spatial component, provides a soil-based tool to maximize crop production under the constraints of environmental legislation.

3.4 Conclusions

1. Soil characterisation in terms of functional properties should be considered as an alternative to traditional 'taxonomic' characterisation when producing soil information for PA. Soil functionality, in this respect, should be expressed in relation to growth limiting factors that can be influenced by precision management (*e.g.*, water and nutrients).
2. The proposed methodology for soil characterisation proved efficient in describing the spatial variability of selected functional properties. Coefficients of determination always exceeded 65%, meaning that less than 35% of the spatial variation was lost through generalisation. Functional units are therefore considered suitable entities to be used as management units for PA.
3. Selecting soil functional properties is a subjective procedure that should reflect a farmer's objectives. Parameters related to crop production (*e.g.*, sensitivity to conditions of stress) will always be important, but environmental parameters (*e.g.*, nitrate leaching) may be relevant as well. Both were considered in this study.

CHAPTER 4

A Methodology for Precision Nitrogen Fertilisation in High-Input Farming Systems[3]

4.1 Introduction

From 1950 onwards the rapid intensification of agricultural production systems has resulted in a dramatic increase of fertiliser inputs. Apart from boosting crop production to high levels, agricultural emissions to the environment have steadily increased. Nowadays, nitrogen (N) emissions to groundwater and surface waters are a major concern in many regions. Given the fact that agriculture is the main source of these emissions, the European Community (EC) has launched several directives to "reduce water pollution caused or induced by nitrates from agricultural sources" (EC-Council Directive, 1991). Stimulated by these directives, individual countries are in the process of implementing a series of policies to tighten environmental constraints. In the Netherlands this has resulted in an N accounting system referred to as *MINAS*. The system will be used to charge levies on budgetary N surpluses at the farm level and is scheduled for gradual implementation over the period 1998-2002. The final objective is to meet the 1980 EC-Drinking Water Directive in both groundwater and surface waters by limiting nitrate concentrations to 50 mg NO_3^- per litre (= 11.3 mg N l^{-1}).

Given the complexity of N dynamics in soils, it remains questionable whether a relatively simple accounting system will suffice to control N losses. Several important processes, such as the net-mineralisation of N from soil organic matter (SOM), are difficult to quantify and therefore excluded from the input-output budgets (so called *farm-gate approach*). Empirical thresholds for levy-free N surpluses are fixed at preset values (e.g., 100 kg N ha^{-1} for arable land in 2003) (Oenema *et al.*, 1997) irrespective of soil heterogeneity and weather conditions.

A flexible and mechanistic approach to fertiliser management, applying knowledge on fundamental processes and incorporating different sources of variability, could increase control over N emissions. This would enable farmers to stay within the limits imposed by current and future generic policies. Agricultural research should explore these concepts in the process of (further) developing economically viable and environmentally sound management systems. Precision agriculture offers great potential in this respect: adapting farm management to the specific conditions at any time and location will significantly improve fertiliser use efficiency.

This paper presents a methodology to optimise N fertilisation, along with the results of a fertiliser experiment conducted during the 1998 growing season. The methodology is embedded within the development of a decision support system

[3] *Published as*: Van Alphen, B.J., and J.J. Stoorvogel. 2001. A methodology for precision nitrogen fertilisation in high-input farming systems. Precision Agriculture 2:319-332.

(DSS) for precision agriculture, which focuses on arable farming and reflects Dutch conditions. The DSS is designed for high-input farming systems with repetitive treatments throughout the growing season (e.g. split fertilisation). For this reason timing is considered equally important as spatial precision. An extensive outline of the DSS was presented by Bouma *et al.* (1999).

The presented methodology uses a mechanistic simulation model to quantify soil mineral N levels and N uptake rates on a real-time basis. Early warning signals are generated once N concentrations drop below a dynamic threshold level, which is defined in relation to actual uptake rates. Spatial variation is incorporated through the concept of management units (Van Uffelen *et al.*, 1997) following procedures developed by Van Alphen and Stoorvogel (2000). They identified spatial units at the field level, each with relatively homogeneous characteristics in terms of water regimes and N dynamics. Simulations are conducted for selected representative soil profiles (one point-simulation for each management unit).

4.2 Materials and Methods

4.2.1 Study area and experimental field

The study was conducted on a commercial arable farm in the central-western part of the Netherlands (51°17'N, 4°32'E). The farm covers an area of approximately 100 ha and applies a crop rotation of winter wheat, consumption potato and sugar beet. Soils originate from marine deposits and are generally calcareous with textures ranging from sandy loam to clay. They are characterised as fine, mixed, mesic Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50,000 soil map (Vos, 1984). With excellent drainage conditions, the area is considered prime agricultural land.

The fertiliser experiment was conducted on a 10 ha field seeded to winter wheat (*Triticum aestivum* L.) in November 1997. Soils were the most prominent source of variability, as expressed through differences in topsoil texture (29% ≤ clay content ≤ 48%) and subsoil composition (peat or mineral matter). SOM contents found in the topsoil were typical for arable land (2-3% SOM) and showed little spatial variation.

4.2.2 Soil database

In the spring of 1997, a detailed 1:5,000 soil survey was conducted in the study area (approximately six soil auger observations per hectare). Results were stored in a soil database containing soil physical and soil chemical properties for individual soil layers. Texture and SOM content were estimated directly in the field and tested against a limited number of laboratory measurements to ensure accurate characterisation. Based on these properties, soil layers were grouped into relatively homogeneous classes defined by the *Staringreeks* (Wösten *et al.*, 1994). This classification distinguishes between topsoil and subsoil layers, which are further differentiated by textural composition and SOM content. Sixteen classes were identified and sampled in the field. Average bulk density and saturated moisture content were determined for each class using at least 4 replicate samples.

Soil hydraulic characteristics were derived through a continuous pedotransfer function (PTF) developed at the DLO-Staring Center (Wösten *et al.*, 1998). The PTF is based on soil physical measurements for 620 soil samples collected from major soil types in the Netherlands. It relates basic soil properties such as texture, SOM content and bulk density to a set of Van Genuchten parameters (Van Genuchten, 1980) describing the moisture retention and hydraulic conductivity curves for individual soil layers. A sensitivity analysis by Vanclooster *et al.* (1992) identified the saturated moisture content as the most sensitive parameter affecting nitrate leaching from a Typic Hapludalf (Soil Survey Staff, 1998). Considering their results, measured saturated moisture contents were used to replace the PTF estimates.

Soil mineral N levels in the experimental field were sampled at monthly intervals. Starting in February 1998 and continuing throughout the growing season samples were collected at 9 sites and at two depths (0-30cm and 30-60cm). Nitrate N, ammonia N and total N were measured in a 50 ml KCl (1 *M*) soil extract using the Technicon-Auto-Analyzer II. The February samples were used to initialise the simulation model. Groundwater levels were measured weekly at two sites located on different subsurface materials (peat and mineral matter). Finally, measured soil moisture contents were available from three monitoring sites that had been installed in the study area the growing season prior to the experiment (1997). Data consisted of weekly measurements collected at two depths (approximately 15cm and 45cm) using Time Domain Reflectometry.

4.2.3 Simulation model

Dynamic simulations of soil-water-plant interaction were conducted with the mechanistic, deterministic simulation model *WAVE* (Water and Agrochemicals in soil and Vadose Environment) (Vanclooster *et al.*, 1994). WAVE integrates four existing models describing: one-dimensional soil water flow (SWATRER) (Dierckx *et al.*, 1986), heat and solute transport (LEACHN) (Hutson & Wagenet, 1992), N cycling (SOILN) (Bergström *et al.*, 1991) and crop growth (SUCROS) (Spitters *et al.*, 1988). Differential equations governing water movement and solute transport are solved using a finite difference calculation scheme. For this purpose soil profiles were divided into one-centimetre compartments. Water movement is described by the Richards' equation (Richard, 1931), which combines the mass balance and Darcian flow equations.

Verhagen (1997) made two conceptual changes to the original model:

1. Water uptake by plant roots was originally modelled assuming preferential uptake in the upper soil compartments. As roots in the deeper layers were hereby excluded, water uptake is now calculated as an integral over the entire root zone.

2. Nitrogen uptake is controlled by N concentrations in the leaves. Originally, this concentration had to be specified as model input. After revision, N concentrations are calculated as a function of biomass production following an empirical relation described by Greenwood *et al.* (1990):

$$N_c = 5.7 \times W^{-0.5}$$

in which N_c is the critical N concentration in the leaves [%] and W is the total weight of accumulated biomass [tons of dry matter ha^{-1}].

Stress resulting from N deficiency occurs when critical N concentrations in the leaves cannot be sustained by N uptake. In this case crop production is reduced proportionally to the ratio of actual over required N concentrations. Water stress is calculated according to Feddes *et al.* (1978). Maximum water uptake is defined by a sink term [d^{-1}], which is considered constant with depth. Water uptake is reduced at high- and low-pressure head values according to crop-specific thresholds.

4.2.4 Management units

Soil variability in the experimental field was described through the concept of management units (Van Uffelen *et al.*, 1997). These units form the basis for precision management and were delineated following procedures developed by Van Alphen and Stoorvogel (2000).

The applied methodology characterizes soils in terms of *functional properties* related to water regimes and N dynamics. These properties are derived through multiple simulations for individual soil profiles (point simulations). Basic soil data required for this purpose (*e.g.*, hydraulic characteristics, SOM content, bulk density) were available for 90 soil profiles in the experimental field. Based on this information, two series of simulations were conducted to describe soil behaviour under the extreme conditions of a dry year (1989) and a wet year (1987). Winter wheat was chosen as a reference for crop growth simulation using model parameters from Spitters *et al.* (1988) and Boon-Prins *et al.* (1993). Management parameters specifying the timing and amount of mineral fertiliser applications were defined according to general practice (240 kg N ha^{-1} distributed over 4 split applications). Four functional properties were considered:

1. Water stress in a dry year;
2. N stress in a wet year;
3. N leaching from the root zone in a wet year;
4. Residual N content at harvest in a wet year.

The first two properties reflect the sensitivity of a soil to the effects of major growth limiting factors. Their direct relation to crop production makes them relevant

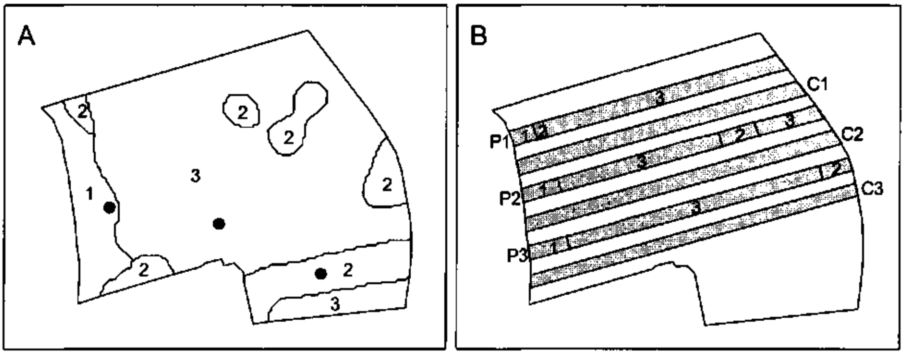

Fig. 4.1. Experimental field. (A) management units 1-3 with representative soil profiles (•); (B) trial strips (P1-P3) and reference strips (C1-C3). Trial strips are subdivided by management units and sections are coded accordingly.

from an economical perspective. Properties three and four were included as environmental parameters, describing the pace at which nitrates are leached from the root zone.

Soil profiles were grouped into functional classes using a multivariate fuzzy c-means classifier. Three classes were identified, following from an objective data set analysis based on so-called *validity measures* (Roubens, 1982). These measures indicate the number of classes that best reflects a balance between structure and continuity (or fuzziness) that is generally pursued (McBratney and Moore, 1985). The appropriate number of classes is thus derived from the data set, thereby eliminating an important source of subjectivity from the classification.

Ordinary kriging (Journel and Huybregts, 1978) and a boundary detection algorithm were used to interpolate class information (point data) and delineate functional units in the experimental field (Fig. 4.1-A). Three units were identified, each representing a spatial grouping of soil profiles with similar functional properties (*i.e.*, belonging to the same functional class). Profiles best matching the average functional properties of their class were selected as representative soil profiles. Average properties and coefficients of determination achieved through spatial grouping are presented in Table 4.1. Together, functional units explained over 68% of the spatial variation, making them suitable entities to be used as management units for precision agriculture.

4.2.5 Experimental setup

Six strips were identified in the experimental field along tramlines used by farm machinery (Fig. 4.1-B). Strips P1-P3 were selected as trial strips receiving precision N fertilisation. Strips C1-C3 were used as reference strips receiving conventional

Table 4.1. Average soil functional properties (± SD) of the functional classes in the experimental field; R^2 indicates the percentage of spatial variation explained by the functional units.

Class	Count[a]	Water stress[b]	N stress[c]	N leaching	N residual
				kg N ha^{-1}	
1	18	0.85 (0.03)	1.00 (0.00)	30.7 (1.6)	93.1 (5.8)
2	9	1.00 (0.00)	1.00 (0.00)	33.1 (1.7)	80.1 (2.6)
3	63	1.00 (0.00)	1.00 (0.00)	38.8 (1.7)	91.1 (2.8)
R^2(%)		92	100	77	68

[a] Count indicates the number of soil profiles grouped in each class.
[b] Water stress is expressed as the ratio of actual over potential evapotranspiration (unit value indicating the absence of stress).
[c] N stress, reflecting the ratio of actual over required N percentages in the leaves, never occurred under the selected management settings and was therefore not a discriminating factor.

fertilisation. Each strip was 16m wide, corresponding to the working width of the fertiliser spreader (8m to each side). Trial strips were further sub-divided by management units among which fertiliser rates could vary.

4.2.6 Real-time simulations to optimise fertiliser application

During the 1998 growing season, real-time simulations were conducted for each of the management units in the experimental field (*i.e.*, point simulations for representative soil profiles). The simulations quantified soil mineral N levels and N uptake rates on a weekly basis. Boundary conditions for the model were specified in accordance with daily meteorological records from an on-farm weather station. Soil hydraulic parameters and groundwater levels were extracted directly from the soil database.

Soil mineral N levels and N uptake rates were calculated over 0-60cm, corresponding to approximately 2/3 of the root zone. Nitrogen budgets were calculated as the net-resultant of input (fertiliser application, mineralisation from SOM) and output fluxes (crop-uptake, denitrification and leaching). Effects of immobilisation and atmospheric deposition were assumed to be negligible over the period of the field experiment (March to July). Decomposition rates (d^{-1}) for SOM pools were specified after Droogers and Bouma (1997) who conducted incubation experiments for similar soil types in the region.

The threshold level indicating N depletion was defined at twice the uptake rate over the past week. A safety margin was thus introduced to: (i) accommodate for model inaccuracies and (ii) provide a time-span for action in case weather conditions hindered machinery from entering the field. Early warning signals were generated once soil mineral N levels dropped below the threshold in either of the management units. In reaction, all management units received additional fertiliser using differences among N levels to vary the dosage if appropriate.

Fertiliser rates were determined through exploratory or *forward-looking* simulations. These simulations extended upon the real-time simulations using historical weather data from an *average* year (1994). They were conducted for the time intervals between consecutive applications, starting at the point where an early warning signal was generated. The length of each interval was estimated using a tentative fertilisation schedule, defining the number of applications and their approximate time line. Given the interval, the required amount of mineral fertiliser was calculated and subsequently applied.

4.2.7 Yield measurements

The effects of precision management were evaluated through yield measurements. Separate measurements were conducted for each experimental strip, including total grain weight, average grain moisture content and hectolitre weight. After correcting for moisture variations, grain yields were calculated by dividing the total grain weight per strip (standardised at 16% moisture) by its strip-specific surface area.

4.3 Results

4.3.1 Model validation

Model performance was tested against measurements available in the soil database. Figure 4.2 presents measured and simulated soil moisture contents. Measurements were collected at three monitoring sites installed in the study area during the 1997 growing season. The overall coefficient of determination is 66%. Figure 4.3 presents measured and simulated soil mineral N concentrations. Measurements were collected during the experiment (1998) in order to verify modelling performance before fertiliser recommendations were made. Samples were taken at two depths (0-30cm and 30-60cm) from 9 sites located in the trial strips. Including samples collected two weeks after harvest (day 229), the overall coefficient of determination equals 71%.

4.3.2 Conventional fertiliser application

Reference strips received conventional management according to fertiliser recommendations provided by the Dutch extension service. The basis for these recommendations was established some 20 years ago through extensive field experiments. Induced by the introduction of more productive varieties, fertiliser rates have been increasing over recent years. Nowadays, fertiliser recommendations are aimed at production levels of 12 tons ha^{-1}, assuming 25 kg of mineral N is required for

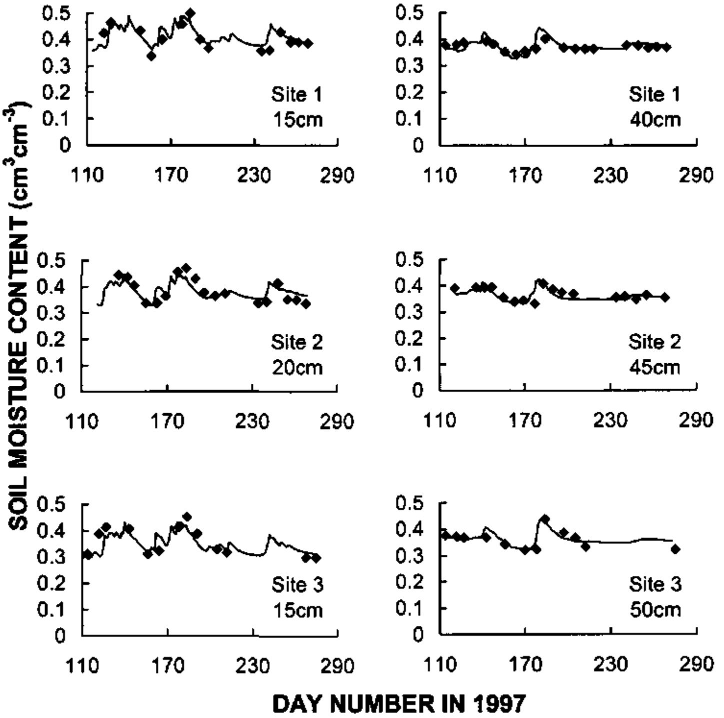

Fig. 4.2. Measured (♦) and simulated (—) soil moisture contents (three sites, two depths).

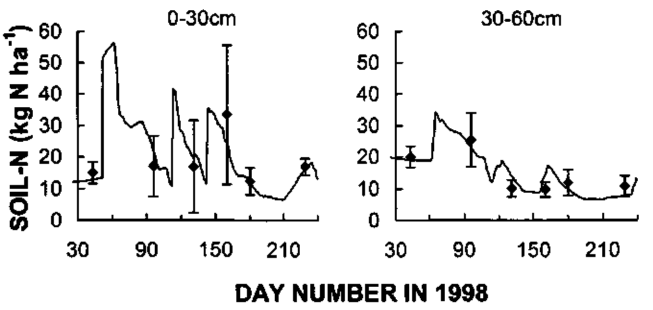

Fig. 4.3. Measured (♦; ± SD) and simulated (—) soil mineral N concentrations. Measurements represent average concentrations derived from 9 sampling sites in the trial strips.

each ton of wheat. Recommendations are provided for individual fields and incorporate average soil mineral N levels measured in the root zone at the start of the growing season. In the experimental field this amounted to 60 kg N ha^{-1} measured in 0-100cm on February 12th. The corresponding fertiliser recommendation (F_r in kg N ha^{-1}) was calculated as:

$$F_r = 300 - N_{min}$$

in which N_{min} is the average soil mineral N *level measured in spring* [kg N ha^{-1} *in* 0-100cm]. This recommendation excluded a top dressing of 40 kg N ha^{-1}, which is traditionally applied just before flowering. The total recommended fertiliser rate was thus established at (300 - 60) + 40 = 280 kg N ha^{-1}.

Mineral fertiliser was applied using a split fertilisation strategy, which has become common practice in the Netherlands. Four applications were scheduled: a base-application in February or March (as soon as farm machinery could enter the field), two applications during April and May (using development stage and colouring as *triggers*) and a top-dressing before flowering in June. With the top dressing fixed at 40 kg N ha^{-1}, remaining fertiliser was distributed evenly over applications one to three (80 kg N ha^{-1} each).

The 1998 growing season started with two relatively warm months. Crop development progressed rapidly and the base-fertilisation was applied early on February 21st. A wet period followed throughout March, allowing the second fertiliser dosage to be applied no earlier than April 23rd. This meant a delay of two weeks compared to the desired schedule: development had progressed beyond the recommended stage and crop colour had become paler. Wet conditions prevailed throughout the remainder of the growing season, resulting in a third and final application on May 20th. By then fungus infestations were detected on leaves and the appearing ears. To avoid further deterioration of crop condition the scheduled top-dressing was cancelled. The total amount of fertiliser was hereby reduced to 240 kg N ha^{-1}.

4.3.3 Precision fertiliser application

Trial strips received precision management based on real-time and exploratory simulations of soil mineral N levels. In line with the reference strips, trial strips received a uniform base application of 80 kg N ha^{-1} on February 21st (day 52). From this point onwards supply and demand for N were analysed on a weekly basis. To account for spatial variability, separate simulations were conducted for each management unit. Figure 4.4 presents simulated soil mineral N levels and weekly N uptake rates for the *critical* unit. This unit showed the most rapid decline of N concentrations and, as a consequence, triggered the early warning signals for N depletion.

The threshold level for N depletion was first reached on April 20th (day 110). Nitrogen concentrations had dropped to 26 kg N ha^{-1} and crop uptake had reached 6 kg N ha^{-1} wk^{-1}. If decision rules had been applied strictly, the threshold level would

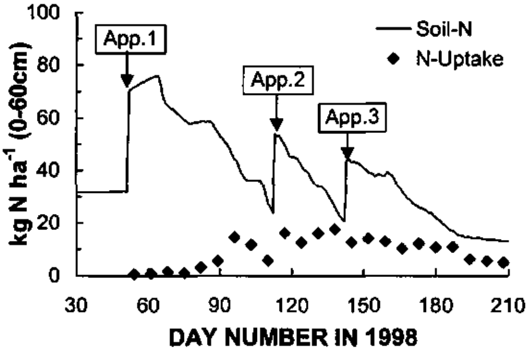

Fig. 4.4. Simulated soil mineral N concentrations and N uptake rates in the trial strips. Fertiliser applications on days 52, 113 and 140 are indicated with *App.1* to *App.3*.

have been set at 12 kg N ha^{-1} (twice the uptake rate) indicating that no action was required. However, uptake had been extremely low as a result of unfavourable weather conditions (low radiation and temperature). Two weeks earlier uptake rates had been up to 14 kg N ha^{-1} wk^{-1} (threshold at 28 kg N ha^{-1}), indicating that action was required under normal conditions. Taking this into consideration, it was decided to apply a second fertiliser dosage on April 23rd (day 113). The fact this coincided with the second application in the reference strips was purely coincidental and caused by weather conditions. The latter application had been planned two weeks earlier, but heavy rainfall had kept machinery from entering the field.

The fertiliser rate for the second application was established at 60 kg N ha^{-1}. This quantity was derived through an exploratory or forward-looking simulation. Starting with the situation on April 20th, the simulation covered a period of four weeks, corresponding to the estimated interval between applications two and three (the latter was scheduled for the second half of May). The calculated rate proved accurate, as threshold levels were reached for the second time on May 18th (day 138). By then soil N concentrations had dropped to 24 kg N ha^{-1} and crop uptake had reached 17 kg N ha^{-1} wk^{-1}. The third application was applied soon after on May 20th (day 140). Again conventional and precision fertilisation coincided, only this time both were applied according to schedule.

The scheduled fourth and final application is traditionally applied just before flowering. This was expected to occur in the second week of June, rendering an estimated time interval of three weeks between applications three and four. A second exploratory simulation was conducted, resulting in a recommended fertiliser rate of 45 kg N ha^{-1} for application three. When flowering was witnessed on June 6th, the fourth application had been cancelled. Fungus infestation was found throughout the field and additional fertiliser would only deteriorate crop condition.

Fertiliser rates applied in trial and reference strips are summarised in Table 4.2. All management units received identical treatment, resulting from low spatial

Table 4.2. Fertiliser rates applied in trial and reference strips.

Date	Trial strips	Reference strips
	kg N ha^{-1}	
February 21st	80	80
April 23rd	60	80
May 20th	45	80
Total	185	240

Table 4.3. Grain yields and hectolitre weights measured in the experimental strips.

Strip	Yield	Hectoliter weight
	tons ha^{-1}	kg hl^{-1}
Trial strips		
P1	8.64	68.4
P2	8.25	68.1
P3	8.06	67.0
Average	8.32	67.8
Reference strips		
C1	8.32	64.8
C2	8.00	64.1
C3	7.80	66.0
Average	8.04	65.0

variability under the specific conditions of the experiment. Simulated soil mineral N levels differed no more than 4 kg N ha^{-1} between the critical and non-critical units. Corresponding to approximately 15 kg of mineral fertiliser (N content = 26%), differences remained just below the resolution of the fertiliser spreader (20 kg). Precision management resulted in a total fertiliser rate of 185 kg N ha^{-1}; a reduction of 55 kg N ha^{-1} or 23% compared to conventional management.

4.3.4 *Measured grain yields*

Grain yields measured in trial and reference strips are presented in Table 4.3. As a result of fungus infestation yields were relatively low compared to normal years. Nevertheless, the total grain yield in trial strips was 3.4% higher than in reference strips ($P = 0.15$). Hectolitre weights, generally used as a quality indicator, were up by 4.4% on average ($P < 0.01$).

4.4 Discussion

By combining real-time simulations with the concept of management units an opportunity is created to optimise N fertilisation in both temporal and spatial dimensions. Fertiliser management becomes more flexible and more accurate: applications no longer rely on recommended rates aimed at maximum production levels (potential yields), but are defined in accordance with the specific conditions during a growing season. Nitrogen applications are triggered by early warning signals for N depletion and fertiliser rates are determined through exploratory or forward-looking simulations. Excessive fertilisation is thus avoided and nitrate emissions are reduced to a minimum. In addition, management becomes pro-active rather than reactive: N deficiencies are alleviated before crop condition is affected.

During the experiment, timing proved a more influential factor than spatial precision. This was caused by the low spatial variability occurring under the specific conditions of the experiment (*e.g.*, susceptibility to drought varied among management units, but water stress never occurred during the wet growing season). Even though this may not be considered a general situation, the experiment does illustrate the relevance of temporal precision in split fertilisation strategies. So far, research has focused mainly on the site-specific variation of single fertiliser dosages applied at the start of the growing season. Rates were varied across fields based on intensive soil sampling, yield measurements or a combination of both (e.g. Ferguson *et al.*, 1997). Timing was not a major issue and, as a consequence, these methods covered only part of the picture.

Fertiliser rates were not varied among management units as soil mineral N levels differed less than the resolution of the fertiliser spreader. Partly this was caused by the specific conditions of the growing season (see remark on the absence of water stress above), but also by the relatively low soil variability in the experimental field. It should however not be concluded that management units are an unnecessary element in the presented methodology. They provide an essential means of limiting the number of real-time simulations required in quantifying the variation of soil mineral N levels across fields. Moreover, many fields contain higher levels of soil variability and different weather conditions (in this case dryer) would have increased differences among units.

Average grain yields were slightly higher in strips receiving precision management. Even though the difference was not statistically significant, it was attained with a substantial reduction on fertiliser input. It may be argued that fungus infestations affected this result. Hand counting of infested grains on July 8th showed a uniform distribution over the field (Fusarium spp. infestation was found on 38% of the grains). Trial and reference strips were therefore equally affected. Interestingly, hectolitre weights were significantly higher in the trial strips ($P < 0.01$). This implies that precision fertilisation, which avoids excessive availability of mineral N, decreased the crops' sensitivity to fungus infestation.

Based on a single experiment, it is impossible to derive general conclusions regarding the economical and environmental performance of the applied methodology. This is not only caused by a lack of data, but also by uncertainty regarding legislative changes in the near future (e.g. height of levies on excess nitrogen). Nevertheless, results indicate that significant reductions on fertiliser input are feasible.

Verhagen and Bouma (1997) showed that leaching during the wet winter season is linearly related to residual N concentrations after harvest. This implies that any reduction on fertiliser input will decrease leaching. Quantifying this effect for the experiment would require further analysis of the specific leaching potential within each management unit. Even though the latter falls outside the scope of this research, the achieved reduction on fertiliser input clearly creates a potential for reduced leaching.

Based on current price levels of mineral fertiliser (≈ 0.5 USD kg^{-1} N) precision fertilisation resulted in a cost reduction of approximately 28 USD ha^{-1}. Even though this is considered relevant, results indicate that higher savings are feasible. First of all, a top-dressing was cancelled that would have increased the benefit of precision over conventional management. Secondly, site-specific fertilisation may improve results in cases where soil variability is higher and/or weather conditions are more discriminating. Finally, environmental effects are not accounted for: EU-countries will start charging levies on nitrogen surpluses in the near future, hereby providing additional economical stimulus for the implementation of more efficient management systems.

4.5 Conclusions

1. The proposed methodology for precision N fertilisation proved efficient in reducing fertiliser inputs (-23%), while slightly improving yields (+3%) and hectolitre weights (+4%). Further research is required to analyse the performance under a wider range of conditions.
2. Even though results are only valid under the specific conditions of the experiment, they clearly illustrate the relevance of precision management as a means to increase fertiliser use efficiency.
3. Real-time simulation of water regimes and N dynamics provides a valuable tool in optimising nutrient management.
4. When focussing on high-input farming systems that apply a split fertilisation strategy, timing should be considered equally important as spatial precision.

CHAPTER 5

A Case Study on Precision Nitrogen Management in Dutch Arable Farming[4]

5.1 Introduction

The European Community (EC) has launched several directives to "reduce water pollution caused or induced by nitrates from agricultural sources" (EC-Council Directive, 1991). Stimulated by these directives, individual EC-members are implementing a series of policies that tighten environmental constraints on agriculture. In The Netherlands this has resulted in a farm-level accounting system for nutrients, which is referred to as *MINAS*. The system is scheduled for gradual implementation over the period 1998-2002 and will be used to charge levies on budgetary nitrogen (N) surpluses. Final objective is to meet the 1980 EC-Drinking Water Directive in shallow groundwater (*i.e.*, maximum concentration of 50 mg NO_3 l^{-1} or 11.3 mg N l^{-1}).

It remains questionable whether a relatively simple accounting system will suffice to control N losses. Several important processes, such as the N-mineralisation from soil organic matter (SOM), are difficult to quantify and therefore excluded from input-output budgets (so called *farm gate approach*). Empirical thresholds for levy-free N surpluses are fixed at preset values (*e.g.*, 100 kg N ha^{-1} for arable land in 2003) (Oenema et al., 1997), hereby neglecting the effect of soil heterogeneity.

A more flexible and mechanistic approach to fertiliser management, applying knowledge on fundamental processes and dealing with different sources of variability, could increase control over N emissions. Precision agriculture offers great potential in this respect: incorporation of spatial and temporal variation will increase fertiliser use efficiency and enable farmers to stay within limits imposed by current and future policies.

A decision support system (DSS) for precision agriculture is currently being developed in The Netherlands (Bouma *et al.*, 1999). The system focuses on arable farming and reflects Dutch conditions. These are characterised by high yields obtained through high inputs of fertilisers and biocides. Management is intensive and dynamic throughout the growing season (winter wheat receives up to 4 consecutive N fertilisations). Designed for this setting, the DSS provides a module to optimise the timing and spatial distribution of consecutive fertiliser applications. Methods applied for this purpose were described by Van Alphen and Stoorvogel (2001[a]). This paper provides a thorough evaluation, based on two fertiliser experiments conducted on different winter wheat fields in consecutive years (1998 and 1999). DSS-based precision management is evaluated in terms of economy (fertiliser input versus grain yield) and environment (soil mineral N residues after harvest). The latter determines

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the potential for leaching of nitrates during winter, as shown by Verhagen and Bouma (1997). In both experiments conventional management served as a reference.

Essentially, the DSS feeds real-time weather data into a mechanistic simulation model to monitor soil mineral N concentrations across a field. Early warning is provided when these concentrations reach a critical threshold. Fertiliser is subsequently applied, using exploratory or *forward-looking* simulations to calculate the required rate. Spatial variation is incorporated through management units (Van Uffelen *et al.*, 1997). These units form the basis for precision management and are delineated following procedures developed by Van Alphen and Stoorvogel (2000). Simulations are conducted for selected representative soil profiles in each management unit.

5.2 Materials and methods

5.2.1 Study area and experimental fields

Fertiliser experiments were conducted on a commercial arable farm in the central-western part of The Netherlands (51.7N, 4.0E). The farm covers an area of approximately 100 ha and applies a crop rotation of winter wheat, consumption potatoes and sugar beet. Soils originate from marine deposits and are generally calcareous with textures ranging from sandy loam to clay. They are characterised as fine, mixed, mesic Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50,000 soil map (Vos, 1984). With excellent drainage conditions, the area is considered prime agricultural land.

Two experiments were conducted on different fields (A and B) and in consecutive years (1998 and 1999). Field A covered an area of 10 ha and provided the setting for the 1998 fertiliser trial. A winter wheat crop (*Triticum aestivum* L.) was sown in November 1997 and harvested in August 1998. Soils formed the most prominent source of variability, expressed through differences in topsoil texture (30% $\leq$ clay fraction $\leq$ 47%) and subsoil composition (peat or mineral matter). SOM contents found in the plough layer corresponded to typical values for arable land (2-3% SOM) and showed little spatial variation.

The second experiment was conducted a year later on field B. This field was larger (16 ha) and contained a higher level of soil variability. Clay fractions varied from 25-50% (0-30cm), with SOM contents ranging from 0.6-5.8% (0-30cm). The same winter wheat variety was grown, this time sown in November 1998 and harvested in August 1999.

5.2.2 Soil database

During the spring of 1997, a detailed 1:5000 soil survey was conducted in the study area. Basic soil properties were collected for 612 geo-referenced soil-sampling sites and stored in a soil database. Texture and SOM-content were estimated directly in the field using hand texture and colour. Estimates were tested against a limited number of laboratory measurements to ensure accurate characterisation. Soil layers were grouped into classes defined by the *Staringreeks* (Wösten et al., 1994). This classification distinguishes between topsoil and subsoil layers, which are further differentiated by textural composition and SOM content. Sixteen classes were identified and sampled in the field. Average bulk density and saturated moisture content were determined for each class using at least 4 replicate samples.

Soil hydraulic characteristics were derived through a continuous pedotransfer function (PTF) developed at the DLO-Staring Center (Wösten et al., 1998). The PTF is based on soil physical measurements for 620 soil samples collected from major soil types in The Netherlands. It relates basic soil properties, such as texture, SOM content and bulk density, to a set of Van Genuchten parameters (Van Genuchten, 1980) describing the moisture retention and hydraulic conductivity curves for individual soil layers. A sensitivity analysis by Vanclooster et al. (1992) identified saturated moisture content as the most sensitive parameter affecting nitrate leaching from a Typic Hapludalf (Soil Survey Staff, 1998). Considering their results, measured saturated moisture contents were used to replace the PTF estimates.

5.2.3 Simulation model

Dynamic simulation of the soil-water-plant system was conducted with a mechanistic, deterministic simulation model named *WAVE* (Water and Agrochemicals in soil and Vadose Environment) (Vanclooster et al., 1994). WAVE integrates four existing models describing: (i) one-dimensional soil water flow (SWATRER) (Dierckx et al., 1986), (ii) heat and solute transport (LEACHN) (Hutson & Wagenet, 1992), (iii) N cycling (SOILN) (Bergström et al., 1991) and (iv) crop growth (SUCROS) (Spitters et al., 1988). Differential equations governing water movement and solute transport are solved with a finite difference calculation scheme. For this purpose soil profiles were divided into 1cm compartments. Water movement is described by the Richards' equation (Richard, 1931), which combines the mass balance and Darcian flow equations. Verhagen (1997) made two conceptual changes to the model:

1. Water uptake by plant roots was originally modelled assuming preferential uptake in upper soil compartments. Roots in the deeper layers were therefore excluded. After revision, water uptake is calculated as an integral over the entire root zone.
2. Nitrogen uptake is controlled by N concentrations in the leaves. Originally, this concentration had to be specified as model input. After revision, N concentrations are calculated as a function of biomass production following an empirical relation described by Greenwood *et al.* (1990):

$$N_c = 57 \times W^{-0.5}$$

in which N_c is the critical N concentration in the leaves [g kg^{-1}] and W is the total dry weight of accumulated biomass [tons ha^{-1}].

Stress resulting from N deficiency occurs when critical N concentrations in the leaves cannot be sustained by N uptake. In this case crop production is reduced proportionally to the ratio of actual over required N concentrations. Water stress is calculated according to Feddes et al. (1978). Maximum water uptake is defined by a sink term [d^{-1}], which is considered constant with depth. Water uptake is reduced at high- and low-pressure head values according to crop-specific thresholds.

5.2.4 Describing soil variability through management units

Soil variability in the experimental fields was described by management units (Van Uffelen *et al.*, 1997). These units form the basis for precision management and were delineated following procedures developed by Van Alphen and Stoorvogel (2000), as summarised below.

Basic soil data were available for 90 (field A) and 81 (field B) soil profiles sampled during the 1997 soil survey. Recorded data included SOM content, bulk density and estimated hydraulic characteristics. Based on this information, two series of simulations were conducted to describe soil behaviour under the extreme conditions of a dry year (1989) or a wet year (1987). Winter wheat was chosen as a reference for crop growth simulation, using model parameters provided by Spitters *et al.* (1988) and Boon-Prins *et al.* (1993). Management parameters, specifying the timing and amount of mineral fertiliser applications, were defined according to general practice (240 kg N ha^{-1} distributed over 4 consecutive applications). Four so-called *functional* properties were quantified for each soil profile:

1. Water stress in a dry year;
2. N stress in a wet year;
3. N leaching from the root zone in a wet year;
4. Residual soil mineral N content at harvest in a wet year.

The first two properties reflect the sensitivity of a soil to the effects of important growth limiting factors. Their direct relation to crop production makes them relevant from an economical perspective. Properties three and four were included as environmental parameters, describing the pace at which nitrates are leached from the root zone.

On a field by field basis, soil profiles were grouped into functional classes using a fuzzy c-means classifier. The number of classes was chosen objectively using so-called *validity measures* (Roubens, 1982). Results varied between fields (three classes in field A versus four classes in field B) reflecting different levels of soil variability. A summary of functional properties is presented in Table 5.1.

Ordinary kriging (Journel and Huybregts, 1978) and a boundary detection algorithm (ESRI, 1998) were finally used to interpolate class information (point data)

Table 5.1. Average soil functional properties (± SD) of the functional classes in fields A and B.

Class	Count[a]	Water stress[b]	N stress[c]	N leaching	N residual
				kg N ha^{-1}	
Field A					
1	18	0.85 (0.03)	1.00 (0.00)	30.7 (1.6)	93.1 (5.8)
2	9	1.00 (0.00)	1.00 (0.00)	33.1 (1.7)	80.1 (2.6)
3	63	1.00 (0.00)	1.00 (0.00)	38.8 (1.7)	91.1 (2.8)
Field B					
1	25	0.99 (0.02)	1.00 (0.00)	29.4 (4.0)	90.1 (4.0)
2	16	0.71 (0.07)	1.00 (0.00)	37.1 (6.6)	106.3 (18.7)
3	30	0.98 (0.04)	1.00 (0.00)	36.8 (3.2)	86.9 (10.7)
4	10	0.96 (0.06)	1.00 (0.00)	56.3 (8.6)	154.5 (15.7)

and delineate functional units in the experimental fields (Fig. 5.1). Each unit represents a spatial grouping of soil profiles with similar functional properties (*i.e.*, belonging to the same functional class). Profiles best matching the average functional properties of their class were selected as representative soil profiles. Together, the functional units explained >70% of the spatial variation in both fields, making them suitable entities to be used as management units for precision agriculture.

5.2.5 Experimental design and field sampling

The experimental design was identical in both experiments. It consisted of six strips positioned along tramlines used by farm machinery (Fig. 5.1). Half of the strips received precision management (P1-P3) and half received conventional management (C1-C3). Each strip was 32m wide, corresponding to the working width of the fertiliser spreader (16m to each side). Precision strips were further sub-divided by management units, among which fertiliser rates were varied.

Soil mineral N concentrations were measured in precision strips at monthly intervals. Separate samples were collected for each management unit differentiating between 0-30cm and 30-60cm. Nitrate N, ammonia N and total mineral N were measured in 50 ml KCl (1 *M*) soil extracts using the Technicon-Auto-Analyzer II (3 replicates). Samples (0-100cm) collected in February 1998 (field A) and March 1999 (field B) were used to initialise the simulation model. Residual soil mineral N (0-100cm) was measured in post-harvest samples collected from all strips. Finally, groundwater levels were measured weekly at the locations of representative soil profiles.

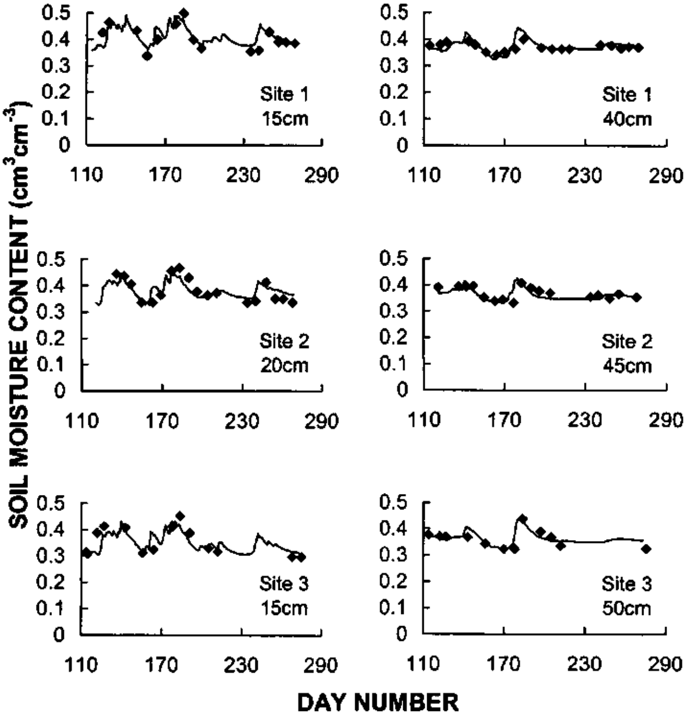

Fig. 5.2. Measured (♦) and simulated (—) soil moisture contents (three sites, two depths).

strip-specific surface area. Weighing of harvested grains was conducted on a nearby weighbridge. Moisture and protein contents were measured in the laboratory using mixed samples from each strip.

5.3 Results

5.3.1 Model validation

Modelling performance was tested against measurements available in the soil database. Figure 5.2 presents measured and simulated soil moisture contents for different depths. Measurements were collected at three monitoring sites installed in the study area in 1997. The overall coefficient of determination is 66%. Figure 5.3 presents measured and simulated soil mineral N concentrations in the critical

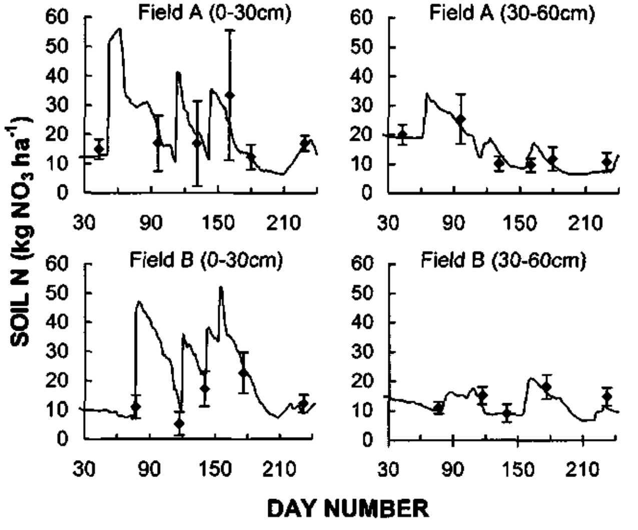

Fig. 5.3. Measured (♦; ± SD) and simulated (—) soil mineral N concentrations in the critical management units of fields A and B. Measurements were collected in experimental strips under precision management.

management units of fields A (1998) and B (1999). The overall coefficient of determination, based on combined data for all management units and both years, equalled 84%.

5.3.2 Fertiliser experiments

5.3.2.1 Field A – 1998

Conventional management. A mixed soil sample was collected on February 17th to measure the average soil mineral N concentration in the root zone: 60 kg N ha^{-1} (0-100cm). The corresponding fertiliser recommendation was calculated as 300 - 60 = 240 kg N ha^{-1}. A top dressing was however excluded, leaving the total recommended rate at 240 + 40 = 280 kg N ha^{-1}. This quantity was partitioned as 80 kg N ha^{-1} to applications 1-3 and 40 kg N ha^{-1} to the top dressing. All fertiliser was applied uniformly.

The 1998 growing season came to a relatively warm start during January and February. Crop development progressed rapidly and the base fertilisation was applied early on February 21st. A wet period followed throughout March, allowing the second application to be performed no earlier than April 23rd. This meant a delay of two weeks compared to the desired schedule: development had progressed beyond the recommended stage and crop colour had become paler. Wet conditions prevailed

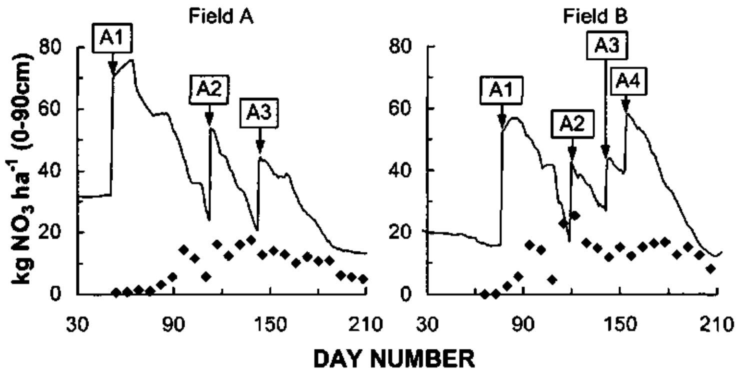

Fig. 5.4. Simulated soil mineral N concentrations (—) and weekly N uptake (♦) in the critical management units of fields A and B. Fertiliser applications are indicated with A1-A3/A4.

throughout the remainder of the season, resulting in a third and final application on May 20th. Soon after, fungus infestations were detected on leaves and the appearing ears. To avoid further deterioration of crop condition the top dressing was cancelled. The total fertiliser input was hereby reduced from 280 to 240 kg N ha^{-1}.

Precision management. In line with conventional management, a uniform base fertilisation of 80 kg N ha^{-1} was applied on February 21st. From this point onwards supply and demand for N were analysed on a weekly basis. Spatial variability was accounted for by conducting separate simulations for management units A1-A3 (Fig. 5.1). Unit A2 turned out to be the critical unit. It showed the most rapid decline of soil mineral N concentrations and, as a consequence, triggered the early warning for N depletion. Simulated soil mineral N levels and weekly N uptake rates are presented in Figure 5.4.

The threshold level for N depletion was first reached on April 20th (day 110). Soil mineral N concentrations had dropped to 26 kg N ha^{-1} and crop uptake equalled 6 kg N ha^{-1} wk^{-1}. If decision rules had been applied strictly, the threshold would have been at 12 kg N ha^{-1} (twice the uptake rate) with no action required. Weather conditions had however been unfavourable (low radiation and temperature) and uptake rates extremely low. Two weeks earlier crop uptake had reached 14 kg N ha^{-1} wk^{-1} (threshold at 28 kg N ha^{-1}) indicating that action was required under normal conditions. Taking this into consideration, it was decided to perform the second fertilisation on April 23rd (day 113). The fact this coincided with a conventional fertilisation was coincidental, as the latter had been delayed for two weeks by heavy rainfall.

With the timing established, a fertiliser rate could be calculated through exploratory simulation. The simulation period was set at four weeks (corresponding to the scheduled interval between applications two and three) and started with the situation on April 20th. Under the assumption of normal conditions the required fertiliser rate was 60 kg N ha^{-1}. It was applied uniformly as soil mineral N concentrations varied too little (< 5 kg N ha^{-1} between units A1-A3) for variable rate application.

The calculated rate proved accurate when the threshold was reached again four weeks later on May 18th (day 138). By then soil mineral N concentrations had dropped to 24 kg N ha^{-1} and crop uptake had reached 17 kg N ha^{-1} wk^{-1} (threshold at 34 kg N ha^{-1}). At this point the time interval between applications three and four was estimated at three weeks (corresponding to the expected time till flowering). A second exploratory simulation was conducted and resulted in a recommended fertiliser rate of 45 kg N ha^{-1}. As differences among units A1-A3 had remained < 5 kg N ha^{-1} the third application was performed uniformly on May 20th (day 140). Again precision and conventional management coincided, only this time both were performed according to schedule.

By the time flowering was witnessed (June 6th), the fourth and final application had been cancelled. Fungus infestations were found throughout the field and additional fertiliser would only deteriorate crop condition. The total fertiliser input therefore remained at 185 kg N ha^{-1}; a reduction of 55 kg N ha^{-1} or 23% compared to conventional management. Fertiliser inputs are summarised in Table 5.2.

Yield measurements and residual N. Average grain yields and hectolitre weights measured in experimental strips are presented in Table 5.3. As a result of fungus infestation yields were relatively low. Nevertheless, total grain yield was 3.4% higher under precision management ($P = 0.15$) and hectolitre weights, generally used as a quality indicator, were up by 4.4% on average ($P < 0.01$). Residual soil mineral N contents (measured in 0-100cm on August 17th) were clearly lower under precision management: 33 (±4) kg N ha^{-1} versus 54 (±6) kg N ha^{-1} under conventional management.

Table 5.2. Fertiliser rates applied under precision and conventional management in field A - 1998.

Date	Precision	Conventional
	kg N ha^{-1}	
February 21	80	80
April 23	60	80
May 20	45	80
Total	185	240

Table 5.3. Grain yields and hectolitre weights measured under precision and conventional management in field A - 1998.

Strip	Yield	Hectoliter weight
	tons ha^{-1}	kg hl^{-1}
Precision		
P1	8.64	68.4
P2	8.25	68.1
P3	8.06	67.0
Average	8.32	67.8
Conventional		
C1	8.32	64.8
C2	8.00	64.1
C3	7.80	66.0
Average	8.04	65.0

5.3.2.2 Field B - 1999

Conventional management. The start of the 1999 growing season was characterised by extreme rainfall. Local depressions were flooded for several days in a row causing severe damage to the crop. Affected areas were however relatively small and well confined. Once the damage proved irreversible, flooded areas were excluded from the fertiliser trial.

Initial soil mineral N concentrations were sampled on March 18th and amounted to an average of 57 kg N ha^{-1} (0-100cm). The corresponding fertiliser recommendation was calculated as 300 - 57 = 243 kg N ha^{-1}. This time a 40 kg N ha^{-1} top dressing was included. The rest was partitioned as 80 kg N ha^{-1} to the base fertilisation and 60 kg N ha^{-1} to applications two and three.

Soils dried rapidly as weather conditions started to improve by the end of January. Machinery could enter the field on March 18th to apply the base fertilisation. Favourable conditions continued hereafter resulting in rapid crop development. Half way through April, crop colour turned slightly paler and triggered the second fertiliser application on April 19th. A consecutive third application was performed within a month (May 14th), again triggered by slight colour alteration. Finally, the top dressing was applied two days before flowering on June 1st.

Precision management. Similar to the previous year, base fertilisations were identical under precision and conventional management: 80 kg N ha^{-1} applied uniformly on March 18th (day 77). From this point onwards supply and demand for N were simulated within management units B1-B3 (Fig. 5.1). Unit B4 could not be included in the experiment as a result of its limited size and position on the outer field boundary. Unit B1 turned out to be the critical unit that triggered early warning for N depletion. Simulated soil mineral N levels and weekly N uptake rates for this unit are presented in Figure 5.4.

The threshold level for N depletion was first reached on April 25th (day 115). Soil mineral N concentrations had dropped to 26 kg N ha^{-1} and crop uptake equalled 23 kg N ha^{-1} wk^{-1} (threshold at 46 kg N ha^{-1}). Within two days the second fertilisation was performed (April 27th), *i.e.*, eight days later than under conventional management. The fertiliser rate was calculated through an exploratory simulation, which started with the situation on April 25th and covered a period of four weeks (corresponding to the estimated interval between applications two and three). It resulted in a recommendation of 55 kg N ha^{-1} for unit B1. Rates for non-critical units were adjusted to correct for larger concentrations of soil mineral N present on April 25th. The difference between units B1 and B3 was however minimal (1 kg N ha^{-1}) and only unit B2 received a lower rate (45 kg N ha^{-1} with 36 kg N ha^{-1} in the soil on April 25th).

With favourable conditions prevailing during the following weeks the time interval to the third fertilisation was shortened. The threshold level was reached a week earlier than anticipated on May 16th (day 136). Soil mineral N concentrations had dropped to 29 kg N ha^{-1} and crop uptake had reached 15 kg N ha^{-1} wk^{-1} (threshold at 30 kg N ha^{-1}). With flowering expected in the first week of June, the time interval to the top dressing was estimated at three weeks. A second exploratory simulation was conducted and resulted in a recommended fertiliser rate of 35 kg N ha^{-1} for unit B1. Again the rate was only adjusted for unit B2: 25 kg N ha^{-1} with 36 kg N ha^{-1} in the soil on May 16th. The third application was performed on May 21st (day 140), exactly one week later than under conventional management.

The top dressing was finally applied just before flowering on June 3rd (day 154). Timing was thus chosen conventionally, but fertiliser rates were calculated rather than applying the regular 40 kg N ha^{-1}. A third exploratory simulation was conducted for this purpose, starting with the situation on June 3rd and calculating the amount of mineral N required for maximum production under *normal* conditions. The calculated rates were 35, 25 and 30 kg N ha^{-1} for units B1-B3 respectively. Total fertiliser input hereby amounted to 205 (B1), 175 (B2) and 200 (B3) kg N ha^{-1}. Compared to conventional management this meant a reduction of 35-65 kg N ha^{-1} or 15-27%. Fertiliser inputs are summarised in Table 5.4.

Yield measurements and residual N. Grain yields and protein contents measured in experimental strips are presented in Table 5.5. Despite wet conditions at the start of the growing season the yield levels were relatively high. No differences were witnessed between precision and conventional management: average grain yield (10.7 tons ha^{-1}) and protein content (134 g kg^{-1}) were equal for both treatments. Soil mineral N residues (measured in 0-100cm on August 20th) were however clearly lower under precision management: 34 (±8) kg N ha^{-1} versus 59 (±9) kg N ha^{-1} under conventional management.

Table 5.4. Fertiliser rates applied under precision and conventional management in field B - 1999. Precision management is specified for management units (MU) B1-B3.

Date	Precision			Conventional
	MU B1	MU B2	MU B3	
	kg N ha^{-1}			
March 18	80	80	80	80
April 19				60
April 27	55	45	55	
May 14				60
May 21	35	25	35	
June 1				40
June 3	35	25	30	
Total	205	175	200	240

Table 5. Grain yields and hectoliter weights measured under precision and conventional management in field B - 1999.

Strip	Yield	Protein content
	tons ha^{-1}	g kg^{-1}
Precision		
P1	11.3	133
P2	10.3	135
P3	10.5	133
Average	10.7	134
Conventional		
C1	11.4	129
C2	10.9	131
C3	10.2	138
Average	10.7	134

5.4 Discussion

During the experiments DSS-based precision management clearly outperformed conventional management in terms of economy (higher fertiliser use efficiency) and environment (lower soil mineral N residues after harvest). The combination of real-time and exploratory simulations resulted in more flexible and more accurate fertiliser management. Input recommendations were no longer based on potential yields (which are seldom obtained), but adapted to actual conditions during the growing season. It was therefore not surprising that fertiliser recommendations provided by the Dutch extension service were too high. It was remarkable, however, that these recommendations were lowered by 40 kg N ha^{-1} in one-year time. Clearly, the extension service is struggling with stricter environmental constraints that are currently being implemented (*e.g.*, the nutrient accounting system *MINAS*).

Besides fertiliser input, timing proved a discriminating factor. This did not apply to the base fertilisation and top dressings, which were triggered by weather conditions (field accessibility in spring) and development stage (flowering). It was also partly obscured in 1998 when unfavourable conditions left only few opportunities for farm machinery to enter the field. In 1999, however, fertiliser was generally applied later under precision management. This implies that early warning for N depletion was provided beyond the point where crop colour turned paler. As yield levels were not affected, it may be concluded that slight alteration of crop colour does not automatically indicate N deficiency. Therefore caution should be taken when using crop colour as a *trigger* in fertiliser management.

Variable rate fertilisation was only applied on field B. It should however not be concluded that the delineation of management units was unnecessary in field A. Management units provide an essential means of limiting the number of real-time simulations required in monitoring soil mineral N levels across a field. The extent to which soil mineral N levels will differ among units depends on the specific conditions during a growing season. This can be illustrated for field A: susceptibility to drought varied among units, but water stress never occurred in 1998. Had a dry period been present then differences among units would have increased, most likely resulting in an opportunity for variable rate application.

Fertiliser rates applied in field B under precision management varied from 175 to 205 kg N ha^{-1}. Differences were mainly related to SOM content, which determines the potential for mineralisation of organic N. Management unit B2, containing 1.8% SOM (0-100cm), consistently received lowest rates. Units B1 and B3, containing 0.9% and 1.2% SOM, received equal rates for applications 1-3. The fourth application was however lower in unit B3. Together, these results illustrate the relevance of incorporating SOM variability into nitrogen management.

It may be argued that fungus infestation affected the results of the 1998 experiment. Hand counting of infested grains on July 8th showed a uniform distribution of Fusarium spp. over the field (infestation was found on 38% of the grains). All experimental strips were therefore equally affected. Interestingly, hectolitre weights were significantly higher under precision management ($P < 0.01$). This implies that by avoiding an excessive availability of mineral N the crop became less sensitive to fungus infestation. Increased resistance against disease should be further analysed as a possible positive effect of precision management.

Verhagen and Bouma (1997) showed that N leaching during winter is linearly related to the residual soil mineral N concentration in the root zone at harvest. In addition, they argued that the average annual precipitation surplus in The Netherlands (300mm) allows for a maximum leaching of 35 kg N ha^{-1} yr^{-1} in order to keep nitrate concentrations in shallow groundwater below 50 mg l^{-1}. With precision management resulting in lower residual N contents it may be concluded that N leaching was reduced. Moreover, a worst case scenario in which N residues leach entirely during winter would still be acceptable under precision management (N residues < 35 kg N ha^{-1} in both experiments). This was certainly not the case for conventional management. Reduced leaching is considered especially relevant since it is a priority issue for both policy makers and farmers.

Based on the current price level of mineral fertiliser (0.5 USD kg^{-1} N), precision management resulted in a cost reduction of 18 - 33 USD ha^{-1}. Even though this is considered relevant, the impact of reduced fertiliser input is much wider. In The Netherlands, the nutrient accounting system *MINAS* is used to charge a levy of 0.7 USD kg^{-1} on budgetary N surpluses > 100 kg ha^{-1} arable land. This creates economical stimulus to stay within the limits of environmental legislation and supports the implementation of precision agriculture. Extra costs associated with precision management are hard to estimate at this time. The soil survey amounted to USD 10000 or USD 100 ha^{-1}. It represents a one-time investment that can be used during many years. The same applies to site-specific equipment that was installed on the fertiliser spreader. Costs were limited to USD 1200 or USD 12 ha^{-1}. Uncertainty remains with respect to the cost of real-time and exploratory modelling. Much depends on who will conduct the modelling: if a farmer can operate a user-friendly computer based DSS the cost will be low. If a modelling service by *e.g.*, the extension service is required the cost will be higher. Exact figures can not be provided at this time.

An unintended but interesting effect that was witnessed relates to the use of animal manure. Dairy farmers are currently paying a 2 USD kg^{-1} N bonus to supply arable farmers with excess manure that cannot be applied on their own pasture (due to levies on N surpluses > 170 kg ha^{-1} pasture). Combining reduced input of mineral fertiliser through precision management with an increased application of animal manure may therefore provide an attractive means of increasing financial returns without exceeding environmental thresholds.

5.5 Conclusions

1. Precision management outperformed conventional management in terms of fertiliser use efficiency. Fertiliser input was reduced by 35-65 kg N ha^{-1} (15-27%) without affecting (1999) or slightly increasing grain yield (1998; $P = 0.15$). Results were consistent over two years and on different fields.
2. Environmental performance was clearly improved by precision management. Residual soil mineral N concentrations remained < 35 kg N ha^{-1}, which was proposed as an environmental threshold by Verhagen and Bouma (1997). Conventional management exceeded this threshold by an average of 22 kg N ha^{-1}.
3. Grain quality was either not affected (1999) or significantly increased (1998; $P < 0.01$) by precision management. The fact that quality improvement coincided with severe fungus infestation points towards a possible positive effect on disease resistance.
4. When developing tools for precision management temporal variation should be considered equally important as spatial variation. This is especially true for farming systems that apply an intensive and dynamic management strategy.
5. Real-time and exploratory simulations proved valuable tools in adapting fertiliser recommendations to the specific conditions of a growing season. Conventional

recommendations, which are targeted at potential yields, were consistently too high.

CHAPTER 6

Effects of Soil Variability and Weather Conditions on Pesticide Leaching - a Farm Level Evaluation[5]

6.1 Introduction

In the late eighties, Leistra and Boesten (1989) found pesticide residues in groundwater bodies across Europe. An extensive review by Ritter (1990) reports similar results for the Unites States. In the Netherlands, groundwater provides an important source of drinking water and its protection is assigned high priority. To improve groundwater quality as well as the quality of natural resources in general, the Dutch government introduced three environmental criteria against which plant protection products must be tested for registration (Health Council of the Netherlands, 2000). These criteria impose limits on persistence in soil (DT_{50}<90 days), leaching into the groundwater (concentration in groundwater < 0.1 $\mu g\ l^{-1}$) and the risk to aquatic organisms (limits on peak concentrations in surface waters based on toxicity levels for fish, *Daphnia*, and algae). These criteria are in line with registration directive 91/414/EEC of the European Union (EU).

An efficient means of assessing pesticide leaching into groundwater is provided by simulation models (Vanclooster *et al*, 2000). As a result, environmental fate modelling now plays an important role in the EU-registration process (FOCUS Groundwater Scenarios Workgroup, 2000). However, problems are encountered when modelling results, which are almost exclusively attained at the point level, are extrapolated to areas. Extrapolation is particularly difficult since pesticide persistence and adsorption have been shown to present great spatial and temporal variation (*e.g.*, Walker *et al.*, 2000). Stoorvogel *et al.* (1999) simulated nematicide leaching from over 400 soil profiles located on a banana plantation in Costa Rica. Leaching proved to be confined to small areas (so called *hot spots*) and to particular periods of the year. Spatial variability was large and could not be described adequately using representative soil profiles for each soil type.

The above illustrates that simulations for one or a few standard scenarios can result in large overestimation of risks associated with pesticide use in a specific region or on a specific farm. Similar simple screening procedures are nonetheless widely applied in pesticide registration throughout Europe (a single scenario is used in The Netherlands and Germany, two scenarios are used in Denmark and nine scenarios have been defined at the EU level). Since the decision making process needs to be pragmatic, a more differentiated approach does not seem feasible at EU or national levels. At the farm level, however, the introduction of precision agriculture offers an opportunity to increase control over pesticide leaching. This is especially relevant in regions where groundwater is exploited as a resource for drinking water.

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In precision agriculture, soil variability is actively managed. Detailed soil information required for this purpose will generally be collected through a specific soil survey (Bouma *et al.*, 1999). When combined with data on pesticide degradation and sorption (either measured or derived from literature), the survey information can be used to model pesticide fate in a large number of soil profiles. Hot spots can be identified and pesticide management can be fine-tuned to avoid excessive leaching to the groundwater.

This study evaluates the effects of soil variability and weather conditions on pesticide leaching. The evaluation is conducted at the farm level and aims at identifying management options that will increase control over groundwater quality. The study area is located on a 100 ha arable farm in the central-western part of the Netherlands. The farmer is an early adopter of precision agriculture technology and has a soil database containing physical and chemical properties for over 600 soil profiles. Pesticide use, which has been documented since 1995, is evaluated following a step-wise approach. First, a relative risk assessment identifies pesticides that pose a relatively high risk to the environment. The assessment is based on simulations for a representative soil profile and uses literature data on pesticide degradation and sorption. Second, the effect of weather conditions is analysed through 20 years of simulations for three distinct soil profiles. Results are summarised in cumulative probability plots of simulated leaching. Third, the effects of soil variability are investigated through simulations for all soil profiles included in the soil database. Simulations are conducted for three pesticides presenting the highest environmental risk. Reference conditions are selected on the basis of the cumulative probability plots derived earlier. Fourth and finally, the point data are interpolated and hot spots are identified as areas where the average pesticide concentration in percolating water exceeds the environmental threshold value of 0.1 $\mu g\ l^{-1}$. Possible implications for pesticide management are discussed at the within-field, field and farm level.

6.2 Materials and Methods

6.2.1 Study Area

Research was conducted on a commercial arable farm in the central-western part of the Netherlands (51°17'N, 4°32'E). The farm covers an area of approximately 100 ha and applies a crop rotation of winter wheat, consumption potatoes and sugar beet. Soils originate from marine deposits, are generally calcareous and have textures ranging from sandy loam to clay. They are characterised as fine, mixed, mesic Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50,000 soil map (Vos, 1984). Soil variability is large and mainly expressed through differences in texture (the average clay content over 0-100cm varies from 14% to 50%), soil organic matter (SOM) content (the average SOM content over 0-100cm varies from 5 g kg^{-1} to 58 g kg^{-1}) and subsoil composition (peat or mineral matter). Drainage conditions are excellent and controlled through a dense system of pipe drains installed at approximately 1-m depth. In general terms, the area is considered prime agricultural land.

6.2.2 Soil Database

During the spring of 1997, a detailed 1:5,000 soil survey was conducted in the study area. Basic soil properties were collected for 612 geo-referenced soil-sampling sites and stored in a soil database. Texture and SOM-content were estimated in the field using hand texture and colour. Estimates were tested against a limited number of laboratory measurements to ensure accurate characterisation. Based on this information, soil layers were grouped into classes defined by the *Staringreeks* (Wösten et al., 1994). This classification distinguishes between topsoil and subsoil layers, which are further differentiated by textural composition and SOM content. Sixteen classes were identified and sampled in the field. The average bulk density and saturated moisture content were determined for each class using at least 4 replicate samples.

Soil hydraulic characteristics were derived through a continuous pedotransfer function (PTF) developed at the DLO-Staring Center (Wösten et al., 1998). The PTF is based on soil physical measurements for 620 soil samples collected from major soil types in The Netherlands. It relates basic soil properties such as texture, SOM content and bulk density to a set of Van Genuchten parameters (Van Genuchten, 1980). These parameters describe the moisture retention and hydraulic conductivity curve and were derived for individual soil layers. A sensitivity analysis by Vanclooster et al. (1992) identified saturated moisture content as the most sensitive hydraulic parameter affecting nitrate leaching. Considering their result, measured saturated moisture contents were used to replace PTF estimates.

6.2.3 Simulation Model

Pesticide fate modelling was conducted using the WAVE-model (Vanclooster *et al.*, 1994 and 1999). WAVE had previously been validated on soil moisture and soil mineral N data from the study area. Van Alphen and Stoorvogel (2000) compared simulated soil moisture contents to weekly TDR measurements for three sites and two depths (20cm and 40cm). The overall coefficient of determination was 66%. Van Alphen (2001) compared simulated and measured soil N data for four soil types and two depths (0-30cm and 30-60cm). The coefficient of determination equalled 84%.

WAVE integrates existing models for one-dimensional water flow (SWATRER; Dierckx et al., 1986) and crop growth (SUCROS; Spitters et al., 1988) with specific modules for heat- and solute transport from LEACHM (Wagenet and Hutson, 1989). The model is mechanistic-deterministic and solves physical transport equations using a numerical finite difference technique. Soil profiles are described in terms of soil horizons, which are divided into 1cm compartments. Mass balances are kept for water, heat and solutes within each compartment, taking into account different sink/source terms.

Water movement is modelled using the Richard's equation (Richard, 1931), which combines the mass balance and Darcian flow equations. Soil hydraulic properties are defined by parametric Van Genuchten equations (Van Genuchten, 1980) and water uptake by crops is modelled after Feddes (1978). Potential uptake is defined by a sink term (d^{-1}) that equals the potential transpiration (mm d^{-1}) divided by the rooting depth (mm). Actual uptake is derived by multiplication with a crop-specific reduction factor [0..1] that reduces uptake rates at high and low pressure head values.

Mass flux of pesticides is modelled using the convection-dispersion equation. In view of the limited availability of non-linear sorption parameters, pesticide retention is described by a simple equilibrium sorption isotherm:

$$X = K_d \; c$$

in which X is amount of pesticide sorbed to the solid phase (kg kg^{-1}), K_d is a linear distribution coefficient (l kg^{-1}) and c is the pesticide concentration in the liquid phase (kg l^{-1}). K_d is generally derived by multiplying the distribution coefficient over organic matter and water K_{om} (l kg^{-1}) with the mass fraction of organic matter in the soil. Pesticide degradation is included through a first order decay model:

$$R = k \; c^*$$

in which R is the rate of degradation (kg l^{-1} d^{-1}), k is the degradation coefficient (d^{-1}) and c^* is the pesticide concentration in the soil system (kg l^{-1}). As proposed by Walker (1974), potential degradation coefficients k_{pot} (d^{-1}) at reference conditions are corrected using:

$$k = f_T f_\theta \; k_{pot}$$

in which f_T is a factor to correct for the influence of soil temperature and f_θ is a reduction factor for the effect of soil moisture conditions. The relation between k_{pot} and the half-life time of a pesticide at reference conditions, DT_{50} (d), is defined by:

$$k_{pot} = \ln 2 / DT50$$

Following Boesten (1986), the factor f_T is described by:

$$f_T = \exp(\frac{T - T_{ref}}{10})$$

in which T is the soil temperature (°C) and T_{ref} is the soil temperature at reference conditions (°C). The factor f_θ is calculated as:

$$f_\theta = \min[1, (\theta / \theta_{ref})^B]$$

in which θ is the soil moisture content (g kg^{-1}), θ_{ref} is the soil moisture content at reference conditions (g kg^{-1}) and B is a constant.

6.2.4 Inventory and Risk Assessment

Pesticide use in the study area has been documented since 1995. Records contain a listing of chemicals (commercial names) used in the different crops. Active ingredients (chemical names) and recommended application rates were derived from the Dutch crop protection guide (Oomen *et al.*, 1999). This document also provided information on specific restrictions applying to some pesticides (*e.g.*, highly mobile compounds are banned from groundwater protection areas).

After the inventory, a relative risk assessment identified pesticides posing a relatively high risk of exceeding the environmental threshold for leaching. The assessment was based on a series of simulations for a representative soil profile reflecting average texture and SOM content in the study area (Fig. 6.1, profile B). Each simulation assumed a standard pesticide application of 1 kg ha^{-1} on April 1^{st}, 1999. Leaching was calculated over a period of one year and expressed as a fraction of the dosage applied. DT_{50} and K_{om} were varied from 1 to 100 (using an interval of 10) with separate runs conducted for each combination. Results were interpolated through ordinary kriging (Journel and Huybregts, 1978) to create a continuous surface of the leaching fraction as a function of DT_{50} and K_{om}.

Literature values of DT_{50} and K_{om} were available for all pesticides used in the study area (Linders *et al.*, 1994). As far as both properties were $\leq$ 100, existing combinations were plotted on the leaching surface. In this way a leaching fraction could be estimated for each compound. Estimates were subsequently combined with recommended application rates to identify pesticides carrying a relatively high risk of exceeding a concentration of 0.1 μg l^{-1} in percolating water. Strongly sorbing compounds ($K_{om} > 100$ l kg^{-1}) were not considered as they present little environmental risk (two compounds with a $DT_{50} > 100$ d were included in this category).

6.2.5 Laboratory and Field Measurements

A series of laboratory and field measurements was conducted to produce validation data for the WAVE model. These data were required to complete the models' validation status, which so far lacked a specific performance analysis for pesticide fate. Measurements were limited to a single pesticide for financial reasons.

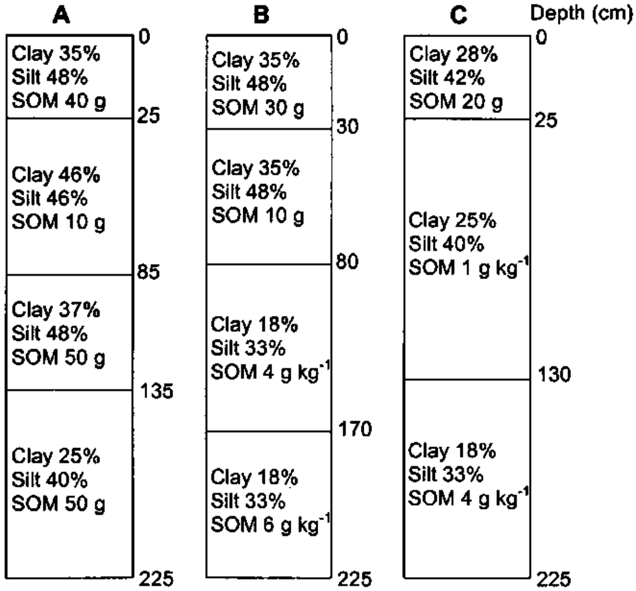

Fig. 6.1. Sampled soil profiles. Profile A combines heavy texture and high SOM% (relatively low-risk for leaching), profile B reflects average properties in the study area (average risk for leaching) and profile C combines light texture and low SOM% (relatively high-risk for leaching). Sand fractions are not included, but equal 100 minus the sum of clay and silt fractions.

Isoproturon, a common herbicide used in winter wheat, was selected for its frequent use in practice and the availability of relatively low cost measurement kits. EnviroGard® Isoproturon Plate Kits (Strategic Diagnostics Inc., Delaware, USA) provide a quantitative laboratory test for the detection of isoproturon residues in soil moisture samples. They resemble ELISA antibody tests and can measure concentrations in the range of 0.05-0.5 $\mu g\ l^{-1}$.

Field measurements were conducted on a single 15.7 ha winter wheat field. Soil moisture samples were taken before isoproturon application on March 20th and again at 4 and 26 weeks after application. Ten sampling sites were positioned strategically across the field to represent textural and SOM variation. Samples were collected using porous cups (10cm length and 2mm diameter) installed at 20cm and 40cm depths. Three sites were also used for groundwater sampling, which was conducted once at 26 weeks after application.

Laboratory measurements determined the DT_{50} and K_{om} of isoproturon. Measurements were conducted in undisturbed 300 cm^3 soil cores collected from three sites at 20 cm and 40 cm depths (3 replicates, 18 samples in total). Sampled soil profiles were selected to reflect textural and SOM variation in the study area (Fig. 6.1, profiles A, B and C). To determine DT_{50}, 1 μg of isoproturon was applied to each soil core. Samples were incubated at 18 °C and moisture contents were maintained by regular additions of distilled water as necessary. At 1, 14 and 28 days the samples were analysed for isoproturon residues. Measurements were conducted in suspensions of 5g fresh soil in 25ml distilled water. The shaking period was set at 24 hours. Gravitational soil moisture contents were determined for each sample through overnight drying in an oven at 110 °C. DT_{50} was calculated through linear regression of log-transformed concentrations (corrected for soil moisture contents) against time.

Sorption characteristics were measured in disturbed samples collected together with the soil cores for DT_{50} (3 sites, 2 depths). Organic C fractions were determined for each sample using an Interscience Elemental Analyser EA1108. Conversion from total C to SOM was made assuming a factor 2.0 for the ratio of SOM to total C (Nelson and Sommers, 1982). Next, 5 g of air-dry soil from each sample was added to 25 ml of respectively a 1, 5 and 10 μg l^{-1} isoproturon solution. The resulting 18 suspensions (6 samples, 3 concentrations) were shaken for a period of 24 hours. K_{om} (l kg^{-1}) was calculated as:

$$K_{om} = \frac{(I_o - I_r)\,W}{S\,I_o\,SOM}$$

in which I_o is the original isoproturon concentration (kg l^{-1}), I_r is the isoproturon concentration recovered after shaking (kg l^{-1}), W is the volume of water (l), S is the amount of soil material (kg) and SOM is the soil organic matter fraction (kg kg^{-1}).

6.2.6 Modelling Pesticide Fate

6.2.6.1 Effect of Weather Conditions

Apart from chemical- and soil properties, the extent to which pesticides leach is largely dependent on weather conditions. Rainfall and evapotranspiration vary greatly between years, resulting in different quantities of percolating water and solute transport. This effect was investigated through twenty years (1980-1999) of simulations for soil profiles A, B and C in Fig. 6.1. Historical weather data (rainfall, temperature and potential evapotranspiration) were available from a regional weather station situated at 20 km distance from the study area. Pesticide application (1 kg ha^{-1} on April 1st) and chemical properties (DT_{50} and K_{om}) were identical in all simulations. The latter were specified using average values measured for isoproturon. Leaching was calculated over a period of one year and expressed as a fraction of the dosage applied.

After completing the simulations, leaching fractions from each soil profile were summarised in cumulative probability plots. The shape of these plots was compared to test the hypothesis that though leaching may differ in absolute terms, the probability increment is independent of soil type. In other words: weather conditions and soil variability act independently on pesticide leaching. Once this hypothesis was confirmed, the year that consistently matched 90% probability was identified (higher leaching occurred in 2 out of 20 years). This year provided the reference conditions for a final series of simulations aimed at evaluating the effects of soil variability.

6.2.6.2 Effect of Soil Variability

Effects of soil variability on pesticide leaching were analysed at the within-field, field and farm level. All profiles in the soil database were included in a simulation series to identify ***hot spots***: areas of land where the average pesticide concentration in percolating water exceeds 0.1 $\mu g\ l^{-1}$. Within the calculation we assume that the groundwater bodies function as a buffer and that the concentrations in groundwater correspond with the average concentration in percolating water. Pesticide leaching was calculated at the point level as: the amount of chemical (kg) transported below 1m depth divided by the total downward flux of soil water (l). Point data were subsequently interpolated using ordinary kriging.

Simulations were conducted for a limited number of compounds identified in the relative risk assessment. Pesticide application was specified after recommendations in the Dutch crop protection guide (Oomen *et al.*, 1999). Meteorological reference conditions were provided by the year matching 90% probability in the probability plots. This introduced a 10% risk level: soils showing up with no or acceptable leaching may exceed environmental thresholds at a maximum of 1 out of 10 years.

6.3 Results

6.3.1 Inventory and Risk Assessment

Table 6.1 presents an overview of pesticides used in the study area during the period 1995-1999. DT_{50} and K_{om} were derived from Linders *et al.* (1994), who compiled average values based on a review of available laboratory measurements.

Figure 6.2 presents simulated leaching from a representative soil profile (Fig. 6.1, profile B) as a function of DT_{50} and K_{om}. Used pesticides are represented by their DT_{50}-K_{om} combinations, which are plotted on top of the interpolated leaching surface. By combining the two sources of information, a leaching fraction was estimated for each compound. Estimates were subsequently multiplied by a recommended application rate and divided by the simulated percolation at 1m depth (531mm). Resulting average concentrations identified isoproturon, metribuzin and bentazon as pesticides presenting a risk of exceeding the threshold concentration (0.1 $\mu g\ l^{-1}$) for percolating water. The risk associated with these pesticides differed, with isoproturon presenting the lowest risk and bentazon presenting the highest risk.

Table 6.1. Pesticides used in the study area during the period 1995-1999. Half-lives (DT_{50}) and sorption coefficients (K_{om}) were derived from Linders *et al.* (1994). Recommended application rates are specified after Oomen *et al.* (1999).

Pesticide	Active ingredient(s)	Type †	Crops ††	DT_{50}	*Kom*	Appl. rate
				(d)	(l kg^{-1})	(kg ha^{-1})
Agil 100 Ec	Propaquizafop	H	P/S	10	242	0.10
Allegro	Epoxiconazole	F	W	280	940	0.12
	Kresoxim-methyl			0.6	120	0.12
Ally	Metsulfuron-methyl	H	W	31	28	0.03
Basagran	Bentazon	H	P	48	0.4	0.96
Curzate M	Cymoxanil	F	P	0.7	10	0.09
	Mancozeb			5	1000	1.36
Isoproturon	Isoproturon	H	W	30	54	1.00
Round Up	Glyfosfate	H	P/W	8	6533	0.72
Sencor WG	Metribuzin	H	P	34	32	0.30
Shirlan	Fluazinam	F	P	107	3225	0.15
Starane	Fluroxypyr	H	W	27	35	0.14
Tattoo C	Chlorothalonil	F	P	10	5031	1.00
	Propamocarb			25	179	1.00
Titus	Rimsulfuron	H	P	31	35	0.01
Topik 240 Ec	Clodinafop-propargyl	H	W	0.6	816	0.05
Tramat	Ethofumesate	H	S	37	84	0.30
Verigal D	Bifenox	H	W	8	1420	0.62
	Mecoprop-P			11	< 1	0.75

† H = herbicide / F = fungicide

†† P = potato / S = sugar beet / W = wheat

6.3.2 Measurements and Model Validation

Isoproturon, on of the three highest-risk pesticides, was selected for field and laboratory measurements. Sorption characteristics measured in disturbed soil samples from profiles A, B and C (Fig. 6.1) resulted in an average K_{om} of 63 (±16) l kg^{-1}. Compared to the average literature value in Table 6.1 this meant an increase of 9 l kg^{-1} or 17%. Sorption did not differ significantly between concentrations considered (1, 5 and 10 μg l^{-1}). Degradation patterns recorded in incubated soil cores are presented in Fig. 6.3. The data are plotted as residual concentrations (in percent) relative to the amount recovered after one day of incubation. Degradation followed first order reaction kinetics with an exponential decrease over time. Linear regression of log-transformed concentrations against time of incubation resulted in an average DT_{50} of 19.4 (±8.9) days. This meant a decrease of 10.6 days or 35% compared to the average

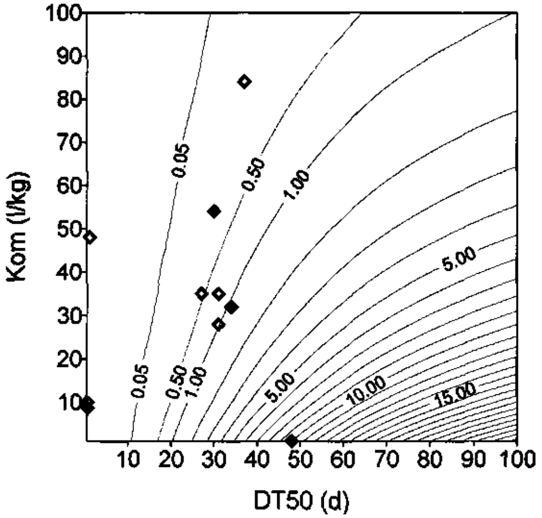

Fig. 6.2. Leaching (in percent) as a function of DT_{50} and K_{om}. DT_{50}-K_{om} combinations of pesticides used in the study area are plotted as: ◊ (leaching ≤ 0.1 μg l^{-1}) or ♦ (leaching > 0.1 μg l^{-1}).

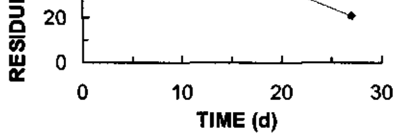

Fig. 6.3. Degradation patterns of isoproturon recorded in incubated soil cores. Samples are coded according to their soil profile (A, B or C) and sampling depth (1 for topsoil, 2 for subsoil). Sample B1 is excluded as pesticide concentrations failed to show a consistent decrease over time.

literature value in Table 6.1. The average gravitational soil moisture content of incubated soil cores was 20 (±2) %. Degradation did not differ significantly between topsoil and subsoil samples.

Isoproturon residues measured in the field were used to validate the WAVE model. Moisture samples collected just before isoproturon application on March 20th showed no signs of an initial concentration present in the soil. Samples collected four weeks later detected isoproturon residues at 20 cm depth (3.13 (±1.14) μg l^{-1}), while no residues were found at 40 cm depth (< 0.05 μg l^{-1}). After 28 weeks, residues were found at both depths: 0.46 (±0.15) μg l^{-1} at 20 cm and 0.29 (±0.03) μg l^{-1} at 40 cm. No residues were detected in groundwater samples at this time (< 0.05 μg l^{-1}).

Field measurements were compared to simulated concentrations for a representative soil profile (Fig. 6.1, profile B). Model input was specified using a combination of measured chemical properties (DT_{50} and K_{om}) and standard parameter settings described by Boesten and Van der Linden (1991). Meteorological data were available from an on-farm weather station. Simulation started on January 1st 2000 with no isoproturon residues in the soil (measured initial condition). Four weeks after application (April 18th), the model calculated concentrations of 3.04 μg l^{-1} (20cm) and 0.0 μg l^{-1} (40cm). This was well within one standard deviation of measured data. Simulated and measured concentrations at 28 weeks after application (October 5th) are presented in Fig. 6.4. Under the assumption that the entire isoproturon dosage (1 kg ha^{-1}) entered the soil environment, the simulation overestimated measured concentrations by approximately a factor 2. This was not surprising since losses during spraying (*e.g.*, spray drift, interception, volatilisation, photochemical degradation) were not considered. For illustration purposes, the simulated concentrations were corrected for crop interception and added to Fig. 6.4. Correction was performed using a simple leaf area index based factor ($\exp(-0.5\ LAI)$) derived for cereals by Gyldenkærne *et al.* (1999). At the time of application, the simulated *LAI* equalled 0.8 $m^2\ m^{-2}$. The corrected application rate (0.67 kg ha^{-1}) reduced the simulated concentrations to a level within one standard deviation of the measured data (verified at 4 and 28 weeks after application).

6.3.3 Modelling Pesticide Fate

Cumulative probability plots of pesticide leaching from soil profiles A, B and C (Fig. 6.1) are presented in Fig. 6.5. Each plot is based on twenty years of simulations (1980-1999) using isoproturon as a reference chemical. Though absolute values differed, the shape of the probability plots was similar among the soils. This confirmed the hypotheses that weather conditions and soil properties act independently on pesticide leaching. The year that consistently matched 90% probability was 1981.

Effects of soil variability on pesticide leaching are reflected in Fig. 6.6. Presented patterns were derived for risk bearing chemicals (isoproturon, metribuzin and bentazon) using 1981 as a reference for simulation. The latter implies that calculated pesticide concentrations in percolating water may be exceeded in 1 out of 10 years (10% risk-level). Pesticide application was specified after Oomen *et al.* (1999): 1 kg ha^{-1} of isoproturon on April 1st, 0.1 kg ha^{-1} of metribuzin on May 1st, May 15th and May 30th (0.3 kg ha^{-1} in total) and 0.48 kg ha^{-1} of bentazon on May 15th and May 30th (0.96 kg ha^{-1} in total). As initial losses could not be quantified unambiguously for all

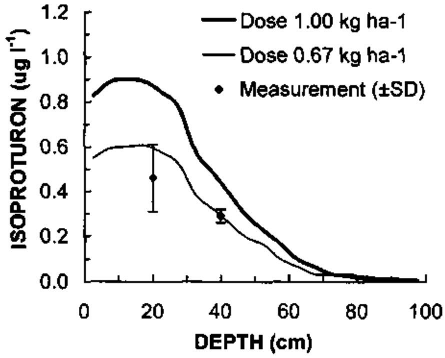

Fig. 6.4. Simulated and measured isoproturon concentrations at 28 weeks after application. Simulated concentrations for the higher dosage (1 kg ha^{-1}) assume no initial losses, whereas the lower dosage (0.67 kg ha^{-1}) accounts for interception losses during spraying.

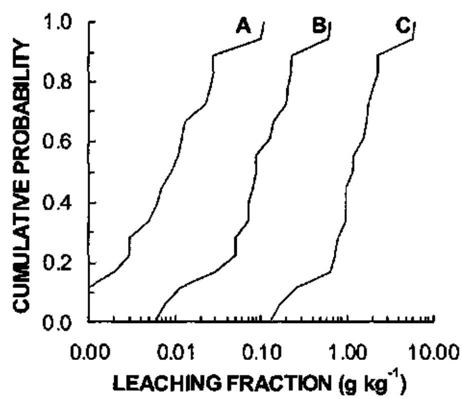

Fig. 6.5. Cumulative probability plots of isoproturon leaching from soil profiles A, B and C. Plotted data refer to simulated leaching fractions for 20 years of data.

three chemicals, the entire dosage was assumed to enter the soil environment. DT_{50} and K_{om} were measured (isoproturon) or specified after literature values (metribuzin and bentazon). At the farm level, simulated average concentrations in percolating water equalled 0.07 (±0.07) μg l^{-1} for isoproturon, 0.20 (±0.11) μg l^{-1} for metribuzin and 6.76 (±0.96) μg l^{-1} for bentazon. Simulated leaching was considered no-risk if average pesticide concentrations remained ≤ 0.1 μg l^{-1}. Concentrations within the

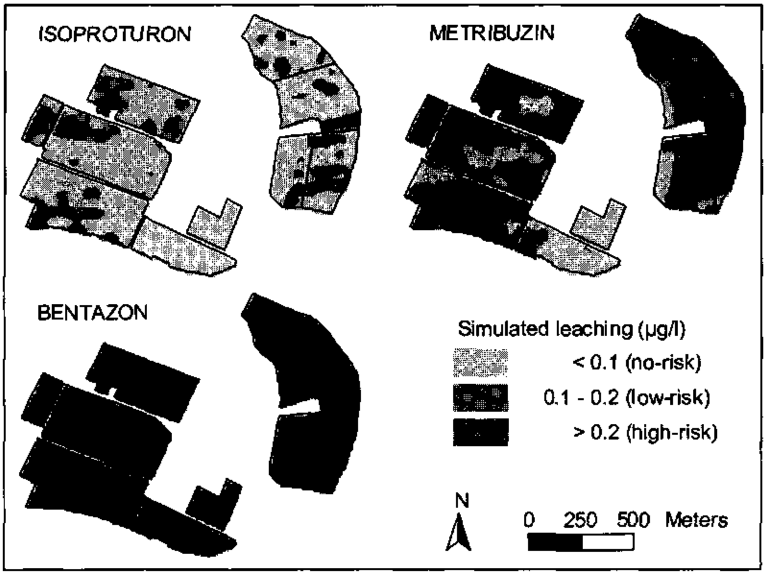

Fig. 6.6. Effects of soil variability on the leaching of isoproturon, metribuzin and bentazon.

range of 0.1 - 0.2 µg l^{-1} were considered low-risk, as initial losses were neglected and validation had indicated an overestimation of measured concentrations. Average pesticide concentrations > 0.2 µg l^{-1} were considered high-risk.

6.4 Discussion

The relative risk assessment, which identified isoproturon, metribuzin and bentazon as higher-risk pesticides, was based on simulated leaching under chosen reference conditions. Soil properties and application dates were fixed. Differences among pesticides originated from chemical properties (DT_{50} and K_{om}) and application rates, not from different periods of application. This pragmatic simplification was required to limit the number of simulations. Its effect is mitigated by the fact that autumn application, which presents a higher risk for leaching, is not practiced in the study area.

Specific attention was required for the validation status of the WAVE model. Results showed that simulated isoproturon concentrations were accurate 4 weeks after application. This was mainly interpreted as a confirmation that downward progression of the pesticide front was accurately modelled. At 28 weeks, however, measured concentrations were overestimated by approximately a factor 2. Performance improved after correction for crop interception, allowing discrepancies to be largely attributed to initial losses. Model performance within the soil environment was considered accurate.

The relevance of initial losses is undisputed, especially for pesticides that are applied after crop emergence. However, quantifying these losses for different pesticides and crops is difficult with the current knowledge (Boesten, 1999). In fact, the pragmatic choice to neglect the processes involved (spray-drift, interception, surface volatilisation and photochemical degradation) may be one of the main reasons that pesticide degradation is generally underestimated by simulation models (Beulke *et al.*, 2000). The correction factor for crop interception, which was used in the validation experiment for isoproturon, is specific to cereals. As metribuzin and bentazon are applied to potato, this factor could not be applied unambiguously. Moreover, crop interception is merely one of several processes causing initial losses. An alternative non-mechanistic way of dealing with initial losses was applied in interpreting simulated leaching patterns (Fig. 6.6). Apart from no-risk and high-risk categories, a low-risk category accounted for concentrations that exceeded the environmental threshold by less than a factor 2. This factor corresponded to the approximate overestimation found during model validation.

The main consideration in analysing the effect of weather conditions was to select a reference set that represented severe, but not extreme leaching. To minimize subjectivity, the selection process was based on cumulative probability plots (Fig. 6.5). These clearly showed that leaching was extreme in 2 out of 20 years (notice the abrupt increase of the leaching fraction between 90% and 95% probability). The year representing severe but non-extreme leaching was selected as the year matching 90% probability. The fact that this introduced a 10% risk-level was considered acceptable.

Effects of soil variability on pesticide leaching were found to be significant, though variable among compounds. Bentazon clearly presented the highest environmental risk. Simulated average concentrations in percolating water consistently exceeded 0.1 $\mu g\ l^{-1}$ and did so at an impressive margin. Due to its low adsorption coefficient (0.4 $l\ kg^{-1}$), spatial variation of simulated leaching was low (the coefficient of variation at the farm level equalled 0.14). Isoproturon presented a very different situation. Spatial variation of simulated leaching was high (coefficient of variation at the farm level equalled 1.00), but concentrations in percolating water only exceeded 0.1 $\mu g\ l^{-1}$ at the within-field level. High-risk areas (or hot spots) were small, well confined and limited to a few fields. Metribuzin presented the most interesting case. Spatial variation of simulated leaching was substantial (coefficient of variation at the farm level equalled 0.55) and concentrations in percolating water exceeded 0.1 $\mu g\ l^{-1}$ at the within-field, field and farm levels. In terms of environmental risk, differences within and among fields were apparent. High-risk areas were found in 9 out of 10 fields. Compared to isoproturon these areas were larger, though still well confined (not scattered). Four fields presented average concentrations $\leq 0.2\ \mu g\ l^{-1}$ (no-risk or low-risk) and six fields exceeded 0.2 $\mu g\ l^{-1}$ (high-risk). The average metribuzin concentration at the farm level equalled the maximum for the low-risk category (0.20 $\mu g\ l^{-1}$).

A key question is how simulated leaching patterns can be used to facilitate precision management of pesticides. Automatically, this raises the issue of scale: at which level (within-field, field or farm level) should the environmental threshold concentration be implemented? Obviously, each scale level has different implications for pesticide management. Implementation at the within-field level requires pesticide concentrations to remain ≤ 0.1 μg l^{-1} everywhere. In the current context this would restrict pesticide use on all fields containing hot spots, irrespective of average field concentrations. Especially in the case of isoproturon this would exaggerate the environmental risk. Implementation at the farm level focuses on average pesticide concentrations calculated for the entire farm. Results would in this case support the use of isoproturon (no-risk) and metribuzin (low-risk). Bentazon (high-risk) would be banned (in fact this chemical is scheduled for removal from the Dutch market by 2004). One can argue that the generalisation inherent to this scale level is undesirable, especially for large farms. Moreover, farm-wide application during a single growing season is unrealistic for most pesticides. A third and intermediate option is implementation at the field level. It seems the most realistic option, as management operations are generally planned and executed at this level. In the current context a field level evaluation would support the use of isoproturon, impose a ban on bentazon and restrict the use of metribuzin. With respect to the latter, several options may be considered. The simplest option would be to allow metribuzin to be used only on no-risk and low-risk fields. High-risk fields (in this case 6 out of 10) should be treated with an alternative less persistent chemical. A more sophisticated approach might involve site-specific application of metribuzin to no-risk and low-risk areas, combined with application of an alternative chemical to high-risk areas. Though technically possible, the simple option seems more feasible.

As a final remark, it should be mentioned that results presented for isoproturon are based on measured chemical properties, whereas results for metribuzin and bentazon are based on average values found in literature. Laboratory measurements for isoproturon differed from literature values by -35% (DT_{50}) and +17% (K_{om}). Various sensitivity analyses of pesticide leaching models have indicated that these parameters (especially DT_{50}) are important (e.g., Jury *et al.*. 1987; Boesten and Van Der Linden, 1991). Ideally, chemical properties of all risk bearing pesticides would have been measured in local soil samples. At present this is very costly and proved unfeasible within this research program. The next best option was to use available measurements and complement these with literature values. Obviously this introduced different levels of uncertainty to be associated with model output. In future, the increased availability of low-cost measurement kits (as used in this study) can help to overcome this limitation.

6.5 Conclusions

1. Out of a total of 19 pesticides, the relative risk assessment identified isoproturon, metribuzin and bentazon as relatively high-risk for leaching. Risk levels differed

strongly, with isoproturon presenting the lowest risk and bentazon presenting the highest risk.

2. Comparison of cumulative probability plots for different soil profiles confirmed that weather conditions and soil properties acted independently on pesticide leaching. Probabilistic characterisation of historical weather data could thus be used to select the reference conditions for pesticide fate modelling.
3. Soil variability proved an influential factor affecting pesticide leaching at the within-field, field and farm levels. Spatial variability was highest for isoproturon, followed by metribuzin and bentazon. Differences were related to sorption characteristics: stronger sorption resulted in higher variation.
4. The presented step-wise evaluation can serve as a basis for identification and precision management of high-risk pesticides. Management implications largely depend on the scale level (within-field, field or farm level) at which the environmental threshold concentration of 0.1 $\mu g\ l^{-1}$ is implemented. A political decision regarding this issue is therefore required.

CHAPTER 7

Fine Tuning Water Quality Regulations in Agriculture to Soil Differences[6]

7.1 Introduction

As long as food production was a major policy objective in post-war Europe, little attention was paid to the environmental side effects of agricultural production. Once food production started to exceed food consumption in the seventies of the twentieth century, the environmental impact of agricultural practices became a growing concern to groups of environmentally conscious citizens and politicians. Environmental protection laws were introduced, but their implementation proved to be slow, painful and difficult.

Though farmers in Western Europe currently constitute less than 5% of the population and their contribution to the gross national product is less than 5%, they still carry considerable political clout. This is partly due to the fact that their activities determine the state of the land in rural areas. Even in a densely populated country as the Netherlands, over 70% of the land is still used for agricultural production. Be that as it may, the question remains acute as to why the change to sustainable, economically viable farming systems is so difficult. The role of research in this overall process deserves special attention, as research should be in a prime position to provide the keys to innovative development.

So far, agricultural research has played a key role in: (i) providing basic data for environmental laws and regulations, (ii) developing policy tools for implementation of environmental regulations and (iii) developing innovative sustainable farming systems. This paper intends to analyse the role of research in the three above areas and provides examples of how research can contribute to a successful implementation of environmental legislation. Attention focuses on the use of nitrogen (N) fertilisers and pesticides, which currently receive ample attention in EU-countries. Presented examples are based on research at a modern arable farm on prime agricultural land in the Netherlands.

7.2 The role of agricultural research

7.2.1 Basic data for environmental laws and regulations

EU-directives increasingly determine the threshold concentrations for agrochemicals in soil and groundwater that are to be implemented at the national

[6] *In press*: Bouma, J., B.J. van Alphen, and J.J. Stoorvogel. Fine tuning water quality regulations in agriculture to soil differences. Journal of Environmental Policy and Planning.

level. Threshold concentrations reflect concentrations that are not harmful to living organisms, including man, even when exposure occurs for an extended period of time. They are generally determined through ecotoxicological dose-effect experiments for a limited number of animal and/or plant species. A well-known threshold is the 50 mg l^{-1} nitrate concentration for drinking water and shallow groundwater (European Commission, 1991[b]). Though often disputed for its weak scientific basis and large assumed safety margins (e.g., Addiscott and Benjamin, 2000), it is the golden standard that has to be dealt with. Similarly for pesticides, a threshold concentration of 0.1 μg active substances l^{-1} is applied to groundwater (European Commission, 1991[a]). This threshold is imposed uniformly, irrespective of the toxicity of specific compounds.

7.2.2 Policy tools for implementing environmental regulations

Well documented threshold concentrations for agrochemicals are not sufficient for environmental regulation. Concentrations found under field conditions are bound to vary greatly in space and time. Aside from being quite costly, measurements are cumbersome and protocols defining the number of samples to be taken and the necessary time intervals are often lacking (*e.g.*, Droogers, 1998). To overcome operational difficulties, emphasis has shifted to the definition of proxy measures. For N fertilisation, the maximum amount of fertiliser that may be applied is being prescribed. EU countries limit organic manure application to 170 kg N ha^{-1} yr^{-1} (European Commission, 1991[b]). In the Netherlands, a farm-level accounting system for nutrients is being implemented. The system, which is referred to as *MINAS*, imposes limits on budgetary N surpluses (*e.g.*, 100 kg N ha^{-1} for arable land in 2003) (Oenema *et al.*, 1997) and charges levies when these are exceeded.

For pesticides, the Dutch ministry of agriculture published a multi-year crop protection plan (LNV, 1991) that listed 90 active ingredients that were to be removed from the market by the year 2000. Measured against the uniform principles for risk assessment (European Commission, 1991[a]), these chemicals presented unacceptable environmental risk. After considerable political commotion, involving a close 72 versus 73 vote in Parliament, seven pesticides were classified as indispensable and extended another two years on market. By 2003 the agrochemical industry should have developed environment friendly alternatives for these compounds.

The definition of proxy measures, such as maximum fertilisation rates and reduction of registered pesticides, contributes strongly to making environmental regulations operational. At the same time, the introduction of proxy measures decreases the transparency of regulations, which can cause problems for their implementation.

7.2.3 Innovative farming systems

Application protocols for agrochemicals, such as N fertilisers and pesticides, have traditionally been derived by dose-effect experiments on small field plots. Increasingly, however, the use of agrochemicals is considered in the broader context of an entire farming system. Application of mineral and organic fertilisers will affect plant growth, but may also cause nitrate pollution in groundwater and/or ammonia emissions to the atmosphere. Also, the N concentration in plants may affect the occurrence of pests and diseases, as well as the extent of the damage they cause. Similarly, pesticides may cause pollution of soil and water and may also affect the quality of produce. By studying the entire production system rather than its separate parts, tradeoffs can be made among contrasting demands. Tradeoffs are part of the prototyping procedure that is currently used successfully to design innovative farming systems (Aarts *et al.*, 1999; Vereijken, 1997). Important contributions to prototype analysis can be made by simulation modelling of N transformations and pesticide dynamics in the soil environment (Hack-ten-Broeke *et al.*, 2000; Boesten and van der Pas, 2000). Such analyses are indispensable tools in evaluating whether proxy measures will succeed in keeping nitrate and pesticide concentrations below their respective environmental thresholds. Field experimentation with an adequate number of variants and repetitions is no feasible alternative, for obvious economic and environmental reasons. The evaluation of proxy values is an important objective of this study, as we see that proxy values start to obtain a significance by themselves, thereby obscuring the link with the original environmental threshold concentrations.

7.3 Arable farming on a prime agricultural soil

The implications of agricultural policies and their alternatives will be illustrated for a commercial arable farm in the Netherlands. First, conventional management practices are analysed in relation to current proxy measures for N-fertilisation and pesticide use. Next, alternative management strategies are presented that apply the concepts of precision agriculture. These strategies were developed and tested in the study area. Conventional and precision management are compared by evaluating whether nitrate and pesticide concentrations in soil water (1-m depth) are likely to remain below their environmental thresholds.

7.3.1 Study area

The farm under consideration is commercially run and located in the central-western part of The Netherlands (51°17'N, 4°32'E). It covers an area of 85 ha and applies a crop rotation of winter wheat, consumption potatoes and sugar beet. Soils originate from marine deposits and are generally calcareous with textures ranging from sandy loam to clay. They are characterised as fine, mixed, mesic Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50,000 soil map (Vos, 1984). Soil variability is large and mainly expressed through differences in texture (the average clay content over 0-100cm varies from 14% to 50%), soil organic matter (SOM) content (the average SOM content over 0-100cm varies from 5 g kg^{-1} to 58 g kg^{-1}) and subsoil composition (peat or mineral matter). With excellent drainage conditions, the area is considered prime agricultural land.

7.3.2 Conventional management

7.3.2.1 Nitrogen fertilisation

Conventional fertiliser management is based on recommendations provided by the Dutch extension service. Their recommendations are founded on empirical dose-response relations that were established some 20 years ago. Over time they have been adapted to meet the demands of new and more productive varieties. In the case of winter wheat, production is now targeted at 12 tons ha^{-1}. Fertiliser recommendations (F_r in kg N ha^{-1}) are provided for individual fields and are calculated as:

$$F_{r,wheat} = 300 - N_{\min}$$

in which $N_{\min}$ [kg N ha^{-1}] is the average soil mineral N concentration in the root zone at the start of the growing season. Similarly, recommendations for potato and sugar beet are calculated as:

$$F_{r,potato} = 245 - 1.1 * N_{\min}$$

$$F_{r,sugarbeet} = 200 - 1.7 * N_{\min}$$

The average $N_{\min}$ concentration measured in different fields during the period 1997-1999 amounted to 60 kg N ha^{-1} (0-100cm). Based on this value, the average fertiliser recommendations for winter wheat, potato and sugar beet were 240, 180 and 100 kg N ha^{-1}. Land allocation to the three major crops in rotation was on average: 55 ha. (64%) to winter wheat, 17 ha. (20%) to potato and 14 ha. (16%) to sugar beet. By combining these data, the average recommended fertiliser rate was calculated at 207 kg N ha^{-1}.

Data on N uptake by the crops were available for the period 1997-1999. Farmers have to calculate this uptake and include it on the farm level N balance for *MINAS*. Calculations are conducted by multiplying the total yield of each crop by the average N content measured in samples of the harvested product. In the study area the average N uptake over the period 1997-1999 equalled 157 kg N ha^{-1}.

By subtracting crop uptake from the fertiliser input (mineral and organic fertilisers), the net N loss can be calculated. According to *MINAS* guidelines annual losses on arable land must not exceed 100 kg N ha^{-1} (situation 2003). If losses do exceed this value, a levee of US $2 (equivalent) will be charged for each kilogram of excess N.

Table 7.1. Farm level N balance for the period 1997-1999. N input consists of mineral and organic fertiliser, N output consists of crop uptake and net losses. Levies on N losses > 100 kg N ha^{-1} are fictive, as they are not charged until 2003.

	1997	1998	1999
		kg N ha^{-1}	
Input			
mineral N	221	248	204
organic N	41	60	80
total	262	308	284
Output			
crop uptake	158	159	153
total	258	259	253
Balance			
net N loss	104	149	131
Levy in 2003			
per hectare	US $8	US $98	US $62
farm level	US $680	US $8330	US $5270

The farm level N balance for the period 1997-1999 is presented in Table 7.1. Considering these data, two issues attract attention. First of all, the *MINAS* guidelines for 2003 were clearly exceeded. As future financial consequences are considerable (levies vary between US $680 and US $8330 at the farm level), fertiliser management will have to be adapted to the new regulations. Obviously this means a reduction of the total fertiliser input. A second issue concerns the steady increase of manure application. This effect is driven by financial benefit: dairy farmers are paying arable farmers a US $2 kg^{-1} N bonus to apply excess manure on their land (Dutch dairy farmers generally produce more manure than they can apply on their own pasture).

Based on the above, one may conclude that conventional N management will have to be adjusted before 2003. Assuming that crop uptake will not increase, the maximum fertiliser input will amount to 157 + 100 = 257 kg N ha^{-1}. As manure application provides financial benefit, the entire N quotum will be used annually. Most likely mineral fertiliser will be applied following official recommendations (207 kg N ha^{-1} on average), leaving 50 kg N ha^{-1} to be applied in the form of organic manure. Compared to the situation described in Table 7.1, this means a reduction of 28 kg N ha^{-1} on average. This is hardly a sharp decrease and it remains doubtful whether this will suffice to keep nitrate concentrations in shallow groundwater below the limit of 50 mg l^{-1}.

7.3.2.2 Pesticide use

Pesticide use is controlled through registration procedures at the EU and the national level. During registration, it is determined whether a pesticide may be used and under which conditions. Requirements for EU registration are described in the uniform principles for risk assessment (European Commission, 1991[a]). An important environmental criterion taken into account is leaching to the groundwater. Pesticide concentrations must not exceed 0.1 μg l^{-1} and risks of exceeding this threshold are primarily assessed through simulations for a number of standard scenarios. A scenario, in this respect, refers to a characteristic combination of soil type and weather conditions. At the EU level, nine scenarios are evaluated that represent a variety of soil and weather conditions encountered in Europe (FOCUS, 2000). If all environmental criteria are satisfied for at least one scenario, an active ingredient may be granted access to the European market. However, national registration procedures have the final word in determining whether a chemical may actually be used in a specific country (Rasmussen and MacLellan, 2001). Often this includes a second evaluation of pesticide persistence in soil and risks for percolation to the groundwater. Again simulation studies are conducted for a varying number of characteristic scenarios (*e.g.*, two scenarios are used in Denmark, whereas a single scenario is used in The Netherlands and Germany). Lysimeter experiments may complement simulation results if excessive leaching is suspected.

Pesticides used in the study area are listed in table 7.2. All chemicals have passed EU and national registration procedures and are applied following official recommendations compiled in the Dutch crop protection guide (Oomen *et al.*, 1999). A key question, however, is whether EU and national registration procedures can guarantee that pesticide use is environmentally safe at the farm level?

7.3.3 Alternative management strategies

Alternative management strategies for N fertilisation and pesticide use were developed in the study area by Van Alphen (2001) and Van Alphen and Stoorvogel (2001[a/b]). These strategies apply validated simulation models to translate soil information into guidelines for precision management. In the following paragraphs, precision management is discussed in terms of its effects on the simulated leaching of nitrates and pesticides. Simulation results are compared to conventional management and measured against environmental threshold concentrations for groundwater quality.

7.3.3.1 Nitrogen fertilisation

Van Alphen (2001) conducted two field experiments to compare precision and conventional N fertilisation. The experiments were conducted in consecutive years (1998 and 1999) on two different winter wheat fields. Precision management was

Table 7.2. Pesticides used in the study area during the period 1995-1999. Half-lives (*DT50*) and sorption coefficients (K_{om}) were derived from Linders *et al.* (1994). Recommended application rates are specified after Oomen *et al.* (1999).

Pesticide	Active ingredient(s)	Type †	Crops ††	*DT50*	K_{om}	Appl. rate
				(d)	($l\ kg^{-1}$)	($kg\ ha^{-1}$)
Agil 100 Ec	Propaquizafop	H	P/S	10	242	0.10
Allegro	Epoxiconazole	F	W	280	940	0.12
	Kresoxim-methyl			0.6	120	0.12
Ally	Metsulfuron-methyl	H	W	31	28	0.03
Basagran	Bentazon	H	P	48	0.4	0.96
Curzate M	Cymoxanil	F	P	0.7	10	0.09
	Mancozeb			5	1000	1.36
Isoproturon	Isoproturon	H	W	30	54	1.00
Round Up	Glyfosfate	H	P/W	8	6533	0.72
Sencor WG	Metribuzin	H	P	34	32	0.30
Shirlan	Fluazinam	F	P	107	3225	0.15
Starane	Fluroxypyr	H	W	27	35	0.14
Tattoo C	Chlorothalonil	F	P	10	5031	1.00
	Propamocarb			25	179	1.00
Titus	Rimsulfuron	H	P	31	35	0.01
Topik 240 Ec	Clodinafop-propargyl	H	W	0.6	816	0.05
Tramat	Ethofumesate	H	S	37	84	0.30
Verigal D	Bifenox	H	W	8	1420	0.62
	Mecoprop-P			11	< 1	0.75

† H = herbicide / F = fungicide
†† P = potato / S = sugar beet / W = wheat

based on real-time simulations of soil mineral N concentrations in different management units. Each management unit was characterised by specific soil properties relating to water regimes and N dynamics (Van Alphen and Stoorvogel, 2000). Early warning was provided when soil mineral N concentrations dropped below a critical threshold. Functioning as a trigger, these warnings were used to optimise the timing of four consecutive N fertilisations. Fertiliser rates were determined through exploratory simulations that calculated the amount of mineral N required in each management unit (under the assumption of 'average' weather conditions). Compared to conventional management, precision management reduced fertiliser inputs by 15-27% (35-65 kg N ha^{-1}). Grain yield was either not affected or slightly increased.

Following the methods applied by Van Alphen (2001), the effects of precision management were evaluated at the farm level. Management units were available from Van Alphen and Stoorvogel (2000) and are presented in Figure 7.1. These authors had also successfully validated a mechanistic simulation model denominated WAVE (Water and Agrochemicals in soil and Vadose Environment; Vanclooster *et al.*, 1994).

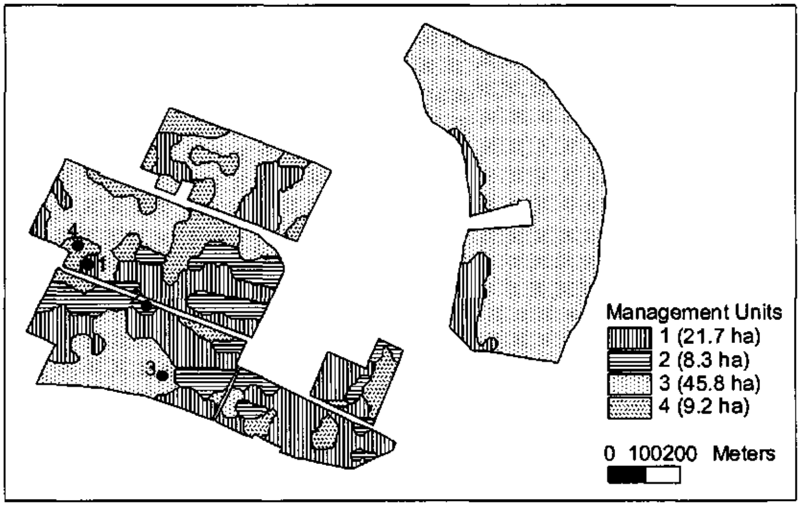

Fig. 7.1. Four management units that were identified in the study area. Locations of representative soil profiles used for simulation are indicated as (•).

Based on representative soil profiles in each management unit, the WAVE model calculated nitrate leaching under conventional and precision management. Winter wheat was chosen as the reference crop and simulations covered a period of one year (April 1st, 1997 to March 31st, 1998). Conventional management was specified such that it reflects the maximum N fertilisation that is acceptable within *MINAS*. Mineral N was applied following official recommendations (240 kg N ha^{-1}) and supplemented with 17 kg N ha^{-1} of organic manure applied just after harvest. Together these applications fill up the MINAS budget defined by crop uptake (157 kg N ha^{-1} on average) and net N losses ($\leq$ 100 kg N ha^{-1}). Precision management - based on real-time simulations of soil mineral N levels – reflected the minimum N fertilisation required for maximum yields. Fertiliser input was fine tuned to the specific conditions in each management unit and manure applications after harvest were left out. Fertilisation rates varied from 150 kg N ha^{-1} (management unit 4) to 190 kg N ha^{-1} (management unit 1). Rates were mainly related to SOM content: higher SOM contents resulted in a higher net-mineralisation of organic N and subsequently in lower N inputs.

Figure 7.2 presents simulated nitrate concentrations in soil water at 1m-depth for both management types. Under conventional management nitrate concentrations consistently exceeded the environmental threshold of 50 mg l^{-1}. The level of exceedance varied, depending on the specific soil properties of each management unit. Precision management resulted in nitrate concentrations < 50 mg l^{-1} for units 1, 2 and 3. In management unit 4, however, the threshold level was exceeded. This was caused

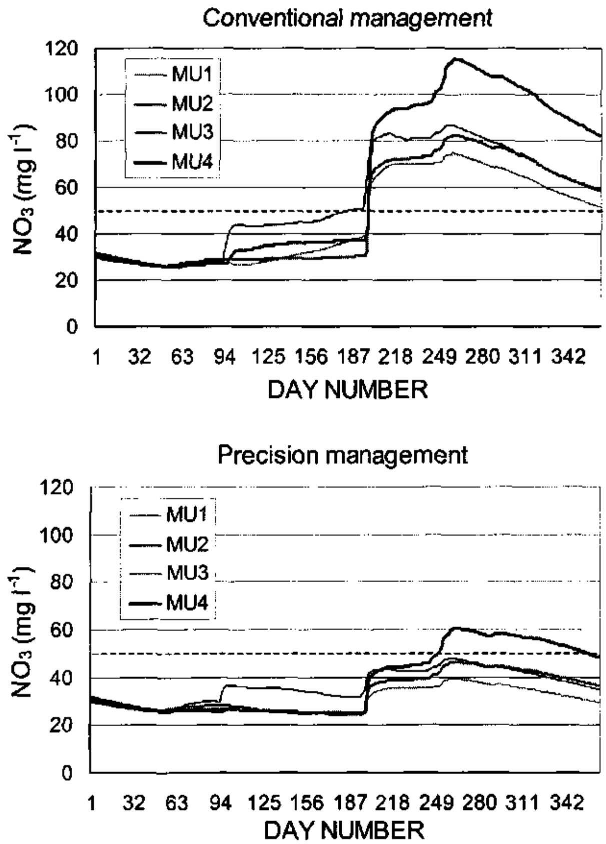

Fig. 7.2. Simulated nitrate concentrations in soil water at 1-m depth (period April 1, 1997 to March 31, 1998). Results are presented for management units (MU) 1 to 4.

by a high SOM content (5% SOM in 0-30cm), which increases leaching through N mineralisation.

Results indicate that compliance to MINAS guidelines does not guarantee that the environmental threshold concentration for nitrate is not exceeded. Precision agriculture reduces nitrate emissions, but the threshold may still be exceeded locally due to soil processes that cannot be influenced by the farmer.

7.3.3.2 Pesticide use

Van Alphen and Stoorvogel (2001[b]) conducted a risk assessment for pesticide use in the study area. They simulated pesticide leaching from over 600 geo-referenced soil

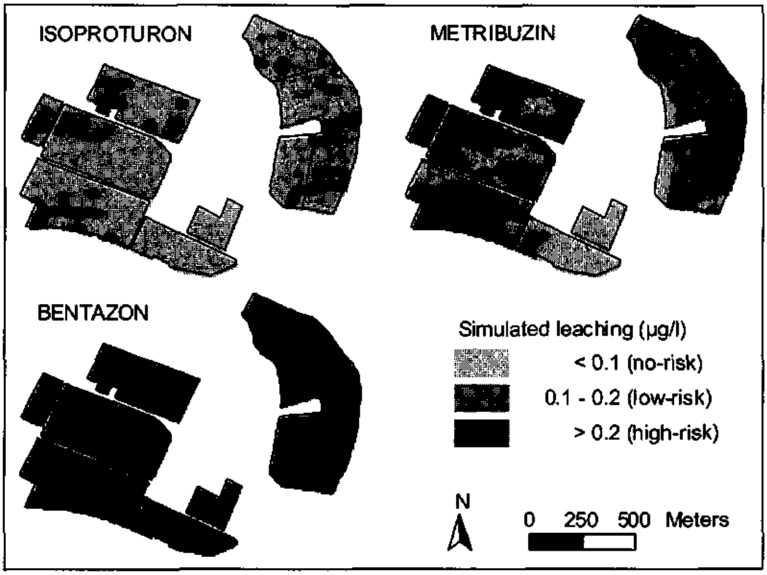

Fig. 7.3. Simulated pesticide concentrations in soil water percolating below 1-m depth (period April 1, 1981 to March 31, 1982).

profiles that were previously sampled. Simulations were conducted using the WAVE model, which was specifically validated in the study area. Out of a total of 19 pesticides (table 7.2), three were identified as relatively high-risk: isoproturon, metribuzin and bentazon. Although all three are approved for use, the risk-level differed strongly among these compounds. This is illustrated by the simulated leaching patterns presented in Figure 7.3. Isoproturon concentrations in percolating water exceed the environmental threshold of 0.1 $\mu g\ l^{-1}$, but only in small well-confined areas. Bentazon showed a more severe pattern with threshold concentrations being exceeded everywhere. Metribuzin presented an intermediate case: excessive leaching on most fields was combined with acceptable leaching on a few.

Results indicate that EU and national registration procedures cannot guarantee that environmental threshold concentrations are not exceeded at the farm, field and within-field level. Especially in areas where threshold compliance is assigned high priority (*e.g.*, areas where groundwater is used as a source of drinking water) the introduction of precision agriculture can help to increase control over pesticide leaching. The risk assessment described above could be used to identify high-risk pesticides and provide guidelines for improved management. With respect to the study area this would imply that bentazon were banned entirely (in fact bentazon is no longer used). Isoproturon presented little risk and precision management should therefore only be considered if threshold compliance is required for every location (currently there is no legislation that prescribes this). Metribuzin does offer opportunities for precision management, both at the field level (application to no-risk fields only) and the within-field level (site specific application to no-risk areas within fields).

7.4 Implications for policy

The environmental indicators for groundwater quality that are currently used in the European Union are broadly accepted. High spatial and temporal variability of contaminant concentrations, as well as budgetary and safety considerations have made it unattractive to verify water quality through repeated measurements. As discussed earlier, this has resulted in the introduction of so-called proxy measures. This study raises questions regarding the level of control that is attained through these measures. Simulation results indicate that threshold concentrations are exceeded while application rates remain within the limits imposed by law. This is undesirable and illustrates the need to keep testing proxy measures in terms of the underlying threshold concentrations for groundwater quality. Calibrated and validated simulation models can be used for this purpose, as illustrated in this study.

The soils found in the study area belong to the best agricultural soils in the Netherlands. If proxy measures do not adequately reflect environmental thresholds in these adsorptive soils, deviations are likely to be more severe in lighter textured soils. A major problem with current proxy measures is the lack of distinction between different soil types. This is being recognised by the regulatory agency in the Netherlands. The *Staatscourant* (the official government paper in which all new laws are presented) of July 6, 2001 (no.128, p.11) presents distinct proxy measures for N fertilisation on sand and loess soils. As no link is made with nitrate contents in the groundwater, this appears to be an ad-hoc and unsatisfactory course of action. The question must be raised whether the time has not come to revise the overall regulatory process making use of modern information technology. This is particularly relevant because the same government paper mentions progress with the official parcel registration program that is due for completion in 2002. The program sets out to register all farmer's fields in the Netherlands in a geographical information system (GIS) that is accessible through internet. Besides geographical data, the system will include information on land use, fertility status and management practices. As most farmers have access to the internet, this new arrangement presents an excellent opportunity to move away from the generic and quite abstract character of current regulations. If farmers can use the system to document and analyse their own management practices, they are likely to be more interested and committed than they are at present. Such a system would also improve the overall transparency of environmental regulations and provide new opportunities for refined control mechanisms. This is very important since the current MINAS system proves to be difficult to run. Recently, the government agency for quality control (De Algemene Rekenkamer) released a highly critical report on the implementation of MINAS, which is way behind schedule. It is in fact virtually impossible to run a top-down control system for some 100,000 farmers, based on highly detailed paper forms that have to be sent to a central office to be processed. It is time now to move ahead and try to implement a system that uses modern information technology. This fits in perfectly well with developments in the field of precision agriculture, which – when supported by a less generic regulatory system – can help to increase control over agricultural emissions.

The shift to a modern, information technology based system that differentiates among soils types will have major implications for soil science. Soil surveys at the farm level will be needed, as described by Van Alphen (2001). Experiences in the study area show that this does not present any problems to the farmer. The investment is relatively minor (US$ 10,000 equivalent for a 100 ha farm) and combined with the parcel registration program mentioned above the farmer will have an excellent new management tool available. This is also important with respect to food quality concerns, which require an ever better documentation of production processes in the food chain. Soil science will have to generate data on N regimes and pesticide dynamics for the major soil units in the Netherlands. Also, running models on a real-time basis to provide management information for farmers may be considered. This procedure was used by van Alphen (2001) when assisting a farmer with implementing precision agriculture in practice. All this will require more study, but should provide a welcome fresh impulse to the soil science profession.

CHAPTER 8

General Conclusions

Describing soil variability

1. Soil characterisation in terms of functional properties should be considered as an alternative to traditional 'taxonomic' characterisation when producing soil information for precision agriculture. Soil functionality, in this respect, should be expressed in relation to growth limiting factors that can be influenced by precision management. Properties related to crop production (*e.g.*, sensitivity to conditions of stress) will always be important, but environmental properties (*e.g.*, leaching potential) are relevant as well. Both were considered in this study, thereby adding an essential element to the work of Verhagen (1997).

2. Simulation models play a key role in deriving soil functional properties from the basic properties collected during a soil survey. The accuracy of the modelling results (and thus of the derived functional properties) largely depends on the availability and the quality of soil hydraulic parameters. These can be estimated accurately and cost-effectively using a combination of continuous pedotransfer functions and (a limited number of) simple laboratory measurements.

3. While the implicit aim of precision agriculture is to treat each site according to its individual requirements, the expense involved in data collection imposes limits on the scale level at which precision management can be implemented. In search of a balance between cost and accuracy, the concept of management units was adopted in this study. Management units proved efficient in describing soil variability at the with-field level and, as a consequence, served as the basic entities for precision N management.

Precision N management

4. Real-time and exploratory simulations (conducted for representative soil profiles in different management units) were successfully used to optimise the timing and the spatial distribution of individual fertiliser applications. Fertiliser management was thus adapted to the specific conditions of a growing season, rather than being targeted at potential yields that are rarely attained.

5. Field trials in winter wheat showed that precision management increased the fertiliser use efficiency. Compared to conventional management fertiliser input was reduced by 15-27% (35-65 kg N ha^{-1}), without affecting or slightly increasing grain yield. Grain quality was either not affected (1999) or significantly increased (1998).

6. By reducing fertiliser inputs, precision management resulted in an improved environmental performance. Residual soil mineral N concentrations (measured in the root zone after harvest) remained below 35 kg N ha^{-1}. This concentration was proposed as an environmental threshold by Verhagen and Bouma (1997). Residual soil N concentrations under conventional management exceeded this threshold by an average of 22 kg N ha^{-1}.

Pesticide management

7. Soil variability proved an influential factor affecting pesticide leaching at the within-field, field and farm levels. Implications of dealing with spatial variability depend on the scale level (within-field, field or farm level) at which environmental threshold concentrations are implemented. A political decision regarding this issue is therefore required.

8. Weather conditions and soil properties were found to act independently on pesticide leaching in the study area. Probabilistic characterisation of historical weather data (in terms of the probability that higher leaching may occur) could thus be used to select reference conditions for pesticide fate modelling.

Implications for environmental regulation

9. Generic proxy measures, such as maximum fertilisation rates and registration procedures for pesticides, cannot guarantee that environmental threshold concentrations for groundwater quality are not exceeded at the farm level. Feasible alternatives to these proxy values are not likely to be found within the context of conventional arable farming. Precision agriculture, however, does present realistic prospects to increase control over nitrate and pesticide emissions. In future it may well be worth to stimulate the introduction of precision agriculture, especially in areas where groundwater is used as a source of drinking water.

General conclusions

10. Results attained in this study confirm the hypotheses proposed in the introduction of this thesis: soil information is crucial to any operational, integrated system for precision agriculture. Soils are a major source of variability and dealing with this variability offers clear opportunities to improve the efficiency of arable farming systems. To fully exploit this potential, an understanding is required of the biophysical processes that govern growth conditions for the crop. Simulation models can be effective tools in this respect, but require high-quality soil information.

11. The objectives as formulated in the introduction were fully achieved. Methodologies were developed to (i) efficiently describe soil variability at the

within-field level and (ii) translate this information into concrete guidelines for precision management. Performing research in a prototyping environment proved successful, as critical and constructive input from the farmers contributed to the development of more realistic and valuable decision support tools.

Summary

The fact that conventional agricultural practices have many detrimental effects is widely acknowledged (Rabbinge, 1997). To mitigate these effects, Dutch policy makers have implemented environmental laws that are essentially based on characteristic indicators for groundwater quality. This has resulted in progressively tighter restrictions on the input of N fertilisers and a consistent reduction of the number of registered pesticides. Enforcement of these laws still creates considerable problems, which is partly caused by their generic character: no provision is made for the significant variation among soil types. As this variation is well known to farmers, their affinity with the imposed rules and regulations is limited. This thesis follows a different approach, in which soil variability is placed at the starting point of research, using the techniques of precision agriculture. The objectives are:

1. Develop a methodology that efficiently describes soil variability at the within-field level. Soil variability should be described in terms of functional properties that are directly relevant to farm management operations. In other words: describe soils in terms of their water regimes, nutrient cycling and sorption characteristics rather than using traditional taxonomic properties such as texture, soil organic matter (SOM) content and colour.
2. Based on the above, develop methods to: (i) optimise the application of N fertiliser and (ii) evaluate and control the environmental risks associated with pesticide use. These methods should be developed through prototyping (Vereijcken, 1997) with ample attention for operational aspects.

In line with the desired setting, research was conducted on a commercial arable farm in the central-western part of the Netherlands (51°17'N, 4°32'E). The farm covers an area of approximately 100 ha and applies a crop rotation of winter wheat, consumption potatoes and sugar beet. Soils originate from marine deposits, are generally calcareous and have textures ranging from sandy loam to clay. They are characterised as fine, mixed, mesic Typic Fluvaquents (Soil Survey Staff, 1998) or Mn25A-Mn45A on the Dutch 1:50,000 soil map (Vos, 1984). Soil variability is large and mainly expressed through differences in texture, soil organic matter (SOM) content and subsoil composition (peat or mineral matter). Drainage conditions are excellent and in general terms the area is considered prime agricultural land.

In order to fully exploit the potential of precision agriculture, an understanding is required of the biophysical processes that govern the growth conditions of a crop. Simulation models provide a powerful tool in this respect and play a crucial role throughout this thesis. To maximize the accuracy of modelling results, much effort was invested in producing high-quality input data. Four methods were compared to derive soil hydraulic parameters from the basic soil properties collected in a 1,5000 soil survey of the study area. Applied methods included: (A) laboratory measurements, (B) class pedotransfer functions, (C) continuous pedotransfer functions and (D) continuous pedotransfer functions combined with simple laboratory measurements. Modelling performance was evaluated by comparing simulated and measured soil moisture contents for three sites and two depths. The combination of

continuous pedotransfer functions and simple laboratory measurements (method D) clearly produced best results. Modelling performance was highest overall and results were consistent for individual profiles and depths. Modelling uncertainty was lowest, far lower than the uncertainty resulting from the measured data set. (Chapter 2)

With the soil hydraulic parameters available, attention focused on describing soil variability. Soils were characterised in terms of simulated functional properties relating to water regimes and nutrient dynamics. Four properties were considered: water stress, N-stress, N-leaching and residual N-content at harvest. Sensitivity to water stress was evaluated for a dry year (1989); other properties were quantified for a wet year (1987). Based on functional similarity, individual soil profiles were grouped into functional classes. Standard interpolation techniques and a boundary detection algorithm subsequently identified soil functional units in each field. Analysis of variance revealed that over 65% of the spatial variation could thus be accounted for. This confirmed that soil characterisation had been efficient and that the resulting units were suitable entities to be used as management units for precision agriculture. (Chapter 3)

Once the management units had been established, two field experiments were conducted to compare precision and conventional N management. The experiments were conducted in consecutive years (1998 and 1999) and on different winter wheat fields (*Triticum aestivum* L.). Precision management used real-time simulations to monitor soil mineral N levels in each management unit. Early warning was provided when mineral N concentrations dropped below a critical threshold. Used as a *trigger*, this information served to optimise the timing of four consecutive N fertilisations. Fertiliser rates were determined through exploratory simulations, which calculated the amount of mineral N required under *normal* conditions. Compared to conventional management, fertiliser input was reduced by 15-27% without affecting grain yield. Grain quality was either not affected (1999) or significantly increased (1998; $P < 0.01$). Soil mineral N residues after harvest were consistently lower under precision management. This is important since leaching of nitrates mainly occurs during winter when a precipitation surplus is present. (Chapters 4 and 5)

Besides N fertilisation, which so far has been the major topic in precision agricultural research, pesticide management received ample attention. A step-wise evaluation was conducted to investigate the effects of soil variability and weather conditions on pesticide leaching. As a first step, a relative risk assessment identified pesticides presenting a relatively high risk to the environment. Second, the effect of weather conditions was analysed through 20 years of simulations for three distinct soil profiles. Results were summarised in cumulative probability plots to provide a probabilistic characterisation of historical weather data. The year matching 90% probability (1981) served as a reference in step three to simulate pesticide leaching from individual soil profiles. After interpolation, areas were identified where pesticide concentrations in percolating water exceeded the environmental threshold of $0.1\ \mu g\ l^{-1}$. Out of a total of 19 pesticides, the risk assessment identified isoproturon, metribuzin and bentazon as relatively high-risk for leaching. Risk levels differed strongly, with isoproturon presenting the lowest risk and bentazon presenting the highest risk. Soil variability strongly affected leaching at the within-field, field and farm levels. Spatial variability was highest for isoproturon, followed by metribuzin and bentazon. Opportunities for precision management were apparent, but depended on the scale level (within-field, field or farm level) at which the environmental threshold is implemented. When legislation is formulated on this issue, the presented step-wise evaluation can serve as a basis for identification and precision management of high-risk pesticides. (Chapter 6)

To synthesize the above, the various studies were discussed in terms of their implications for environmental regulations on groundwater quality. A clear distinction was made between environmental threshold concentrations (50 mg l^{-1} for nitrate; 0.1 µg l^{-1} for pesticides) and proxy measures that are used to enforce these thresholds. Proxy measures applied in the Netherlands include maximum N fertilisation rates and a list of registered pesticides. Simulation results indicated that these measures cannot guarantee that environmental threshold concentrations are not exceeded. Their generic character presents a problem, as different soils show quite different behaviour in terms of N and pesticide dynamics. Feasible alternatives to proxy measures are not likely to be found within the context of conventional arable farming. Precision agriculture, however, does present realistic prospects to increase control over nitrate and pesticide emissions. In future it may well be worth to stimulate the introduction of precision agriculture, especially in areas where groundwater is used as a source of drinking water. (Chapter 7)

Samenvatting

Het feit dat conventionele landbouwkundige praktijken veel ongewenste effecten hebben wordt algemeen erkend (Rabbinge, 1997). Om deze effecten te beperken hebben Nederlandse beleidsmakers milieuwetgeving ontwikkeld, die in wezen is gebaseerd op karakteristieke indicatoren voor grondwaterkwaliteit. Dit heeft geresulteerd in steeds strengere normen voor de toediening van meststoffen en een gestage afname van het aantal toegelaten pesticiden. Het handhaven van deze wetten creëert echter de nodige problemen. Deze zijn deels zijn terug te voeren op hun generieke karakter: er wordt niet of nauwelijks onderscheid gemaakt naar bodemtypen. Aangezien bodemvariabiliteit onder boeren een bekend fenomeen is, beperkt dit hun affiniteit met de huidige regelgeving. Dit proefschrift volgt een andere benadering, waarin - gebruik makend van de technieken van precisielandbouw - bodemvariabiliteit als uitgangspunt wordt genomen. De doelstellingen van het onderzoek zijn:

1. Het ontwikkelen van een efficiënte methode voor het beschrijven van de bodemvariabiliteit binnen landbouwpercelen. De variabiliteit dient beschreven te worden in termen van functionele eigenschappen (waterhuishouding, nutriëntenstromen en adsorptiekarakteristieken) met een directe relevantie voor management operaties.
2. Het ontwikkelen van methoden om: (i) stikstofbemesting te optimaliseren en (ii) de milieurisico's van pesticidengebruik te evalueren. Ontwikkelde methoden dienen via prototyping (Vereijcken, 1997) tot stand te komen, met ruime aandacht voor operationele aspecten.

Overeenkomstig de gewenste setting, is het studiegebied gelokaliseerd op een commercieel akkerbouwbedrijf in zuidwest Nederland (51°17'N, 4°32'E). Het bedrijf beslaat ongeveer 100 ha en hanteert een gewasrotatie van wintertarwe, aardappel en suikerbiet. De bodems zijn van mariene oorsprong en doorgaans kalkrijk met een textuur variërend van zandig leem tot zware klei. Ze worden geclassificeerd als 'fine, mixed, mesic Typic Fluvaquents' (Soil Survey Staff, 1998) of Mn25A-Mn45A op de 1:50,000 bodemkaart van Nederland (Vos, 1984). Er is een hoge mate van bodemvariabiliteit die tot uitdrukking komt in textuurverschillen, organische stof gehalten en de samenstelling van de ondergrond (veen of mineraal materiaal). De bodems zijn goed gedraineerd en in algemene zin wordt het gebied gekwalificeerd als zeer goede landbouwgrond.

Om het potentieel van precisielandbouw volledig te kunnen benutten, is inzage benodigd in de biofysische processen die de groeicondities voor het gewas bepalen. Simulatiemodellen kunnen dit inzicht verschaffen en spelen dientengevolge een centrale rol in dit proefschrift. Om de nauwkeurigheid van de modeluitkomsten te maximaliseren, is veel tijd geïnvesteerd in het vergaren van hoogwaardige invoergegevens. Als basis diende een 1:5,000 bodemkartering van het studiegebied. In aanvulling hierop zijn vier methoden vergeleken om hydraulische parameters af te leiden uit de bodemkundige basisgegevens. Beschouwde methoden omvatten: (A) laboratoriummetingen, (B) klasse pedotransfer functies, (C) continue pedotransfer

functies en (D) continue pedotransfer functies gecombineerd met eenvoudige laboratoriummetingen. De modelprestaties zijn beoordeeld door vergelijking van gesimuleerde bodemvochtgehalten met de gemeten waarden van drie bodemprofielen (meting zijn verricht op twee diepten). De combinatie van continue pedotransfer functies met eenvoudige laboratoriummetingen (methode D) leverde duidelijk de beste resultaten. De modeluitkomsten kwamen het beste overeen met gemeten waarden en vertoonden daarnaast de kleinste onzekerheid. (Hoofdstuk 2)

Met het beschikbaar komen van de hydraulische parameters verschoof de aandacht naar het beschrijven van de bodemvariabiliteit. Bodems zijn gekarakteriseerd in termen van functionele eigenschappen, welke middels simulaties voor individuele bodemprofielen werden afgeleid. Vier eigenschappen zijn in beschouwing genomen: water stress, N stress, N uitspoeling en rest-N na de oogst. Gevoeligheid voor water stress is geëvalueerd voor een droog jaar (1989), de overige eigenschappen zijn geëvalueerd voor een nat jaar (1987). Gebaseerd op functionele overeenkomst zijn de bodemprofielen ingedeeld in functionele klassen. Met behulp van standaard interpolatie technieken en een grensdetectie algoritme zijn vervolgens functionele bodemeenheden binnen alle percelen onderscheiden. Variantieanalyse toonde aan dat meer dan 65% van de ruimtelijke variatie op deze wijze werd verklaard. Dit bevestigde dat de ontwikkelde methode efficiënt is en dat de geïdentificeerde bodemeenheden geschikt zijn als managementeenheden voor precisielandbouw. (Hoofdstuk 3)

De volgende stap in het onderzoek bestond uit een tweetal veldexperimenten, waarin conventionele N bemesting werd vergeleken met precisiebemesting. De experimenten zijn in opeenvolgende jaren (1998 en 1999) op verschillende wintertarwe (*Triticum aestivium* L.) velden uitgevoerd. Precisiemanagement maakte gebruik van zogenaamde 'real-time' simulaties, die de beschikbare hoeveelheid minerale N in de bodem van iedere managementeenheid berekenden. Een waarschuwing werd afgegeven wanneer de bodem-N voorraad beneden een vooraf gedefinieerde grens kwam. Deze waarschuwingen zijn gebruikt om de timing van in totaal vier N-bemestingen te optimaliseren. Verkennende simulaties berekenden vervolgens de toe te dienen hoeveelheid kunstmest, uitgaande van 'normale' condities gedurende de rest van het groeiseizoen. Vergeleken met conventioneel management is de totale kunstmestgift met 15-27% teruggebracht zonder consequenties voor de oogst. De kwaliteit van het geoogste graan werd niet beïnvloed (1999) of zelfs significant verhoogd (1998; $P < 0.01$). Gemeten hoeveelheden rest-N (in de bodem na oogst) waren onder precisiemanagement consequent lager. Dit laatste is van belang, aangezien uitspoeling van nitraat-N voornamelijk plaatsvindt gedurende de wintermaanden (er is dan immers een neerslagoverschot). (Hoofdstukken 4 en 5)

Naast N bemesting - tot op heden het voornaamste onderwerp binnen de precisielandbouw - is uitgebreid aandacht besteed aan pesticidengebruik. Middels een stapsgewijze analyse is onderzocht hoe bodemvariabiliteit en weersomstandigheden de uitspoeling van pesticiden beïnvloeden. De eerste stap bestond uit een risico-analyse waarin pesticiden met een relatief hoge kans op uitspoeling werden geïdentificeerd. De tweede stap omvatte een serie simulaties die de pesticidenuitspoeling berekende voor drie bodemprofielen op basis van 20 jaar aan weergegevens. De resultaten zijn verwerkt in cumulatieve waarschijnlijkheidsplots die 1981 aanwezen als het jaar dat 90% waarschijnlijkheid weerspiegelde (in 90% van de jaren bleef de uitspoeling onder het niveau van 1981). Dit jaar is vervolgens in stap 3 gebruikt voor het simuleren van pesticidenuitspoeling uit individuele bodemprofielen. Na interpolatie konden hiermee gebieden worden geïdentificeerd waar de uitspoeling boven de norm van 0.1 $\mu g\ l^{-1}$ uitsteeg. Als pesticiden met een relatief hoog risicoprofiel werden isoproturon, metribuzin en bentazon aangewezen. Onderling varieerde het risicoprofiel sterk, waarbij isoproturon het laagste en bentazon een hoogste risicoprofiel vertegenwoordigde. Uitspoeling bleek in hoge mate samen te hangen met bodemvariabiliteit. De ruimtelijke effecten waren het grootst voor isoproturon, gevolgd door metribuzin en bentazon. Mogelijkheden voor precisielandbouw waren evident, maar sterk afhankelijk van het schaalniveau (bedrijf, veld, bodemeenheid) waarop de milieuwetgeving van kracht is. Zodra hier politieke duidelijkheid over bestaat, kan de stapsgewijze risicoanalyse dienen als basis voor identificatie en precisiemanagement van pesticiden met een hoog risicoprofiel. (Hoofdstuk 6)

Ter samenvatting van het bovenstaande, zijn de verschillende studies besproken in termen van hun implicaties voor milieuwetgeving op het gebied van grondwaterkwaliteit. Hierbij is een duidelijk onderscheid gemaakt tussen bestaande drempelwaarden (50 mg l^{-1} voor nitraat en 0.1 $\mu g\ l^{-1}$ voor pesticiden) en de maatregelen die worden genomen om deze drempelwaarden te realiseren. Voorbeelden van maatregelen die in Nederland worden genomen zijn het terugbrengen van de maximale bemestingsniveaus en het inkrimpen van de lijst met toegelaten pesticiden. Simulatieresultaten geven aan dat deze maatregelen niet kunnen garanderen dat de milieunormen (vastgelegd in de eerder genoemde drempelwaarden) niet worden overschreden. Een voornaam probleem ligt opgesloten in het generieke karakter van de maatregelen. Er wordt niet of nauwelijks onderscheid gemaakt naar bodemtypen, terwijl deze grote invloed hebben op de N huishouding en het gedrag van pesticiden. Alternatieven voor generieke maatregelen zijn binnen de conventionele landbouw moeilijk te vinden. Precisielandbouw, daarentegen, biedt realistische mogelijkheden om de controle over ongewenste emissies te vergroten. In de toekomst kan het dan ook wenselijk zijn om de introductie van precisielandbouw te stimuleren, met name in die gebieden waar grondwater wordt gebruikt als een bron voor drinkwater. (Hoofdstuk 7)

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Curriculum Vitae

Bertil Jeroen van Alphen werd op 4 februari 1970 geboren in Hoorn. Hij groeide deels op in Spanje (1975-1979), waar hij Engelstalig onderwijs genoot. In Nederland bezocht hij het West-Fries Lyceum en behaalde daar in 1988 het Atheneum diploma.

Aansluitend vertrok hij naar Wageningen om bosbouw te studeren aan de toenmalige Landbouwuniversiteit. Gedurende zijn studie verbleef hij ruim een jaar in Costa Rica en Finland. In 1994 behaalde hij het doctoraal examen, met als afstudeeronderwerp de toepassing van geografische informatie systemen.

Hetzelfde jaar trad hij in dienst bij Heidemij Advies. Hier combineerde hij de advieswerkzaamheden met een deeltijdopleiding hydrologie. Nog voor hij deze opleiding kon afronden werd hij benaderd voor een positie als assistent in opleiding (AIO) bij Wageningen Universiteit. Gedurende de periode 1997-2001 werkte hij bij het laboratorium voor bodemkunde en geologie aan een onderzoek naar de toepassing van bodemkundige informatie in de precisielandbouw.

Sinds mei 2001 is hij in dienst bij de kwantitatieve adviesgroep van PricewaterhouseCoopers. In deze periode is voorliggend proefschrift afgerond.