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Site-specific Management: Balancing Production and Environmental Requirements at Farm Level

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ABSTRACT

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

INTRODUCTION

Sometimes a technological breakthrough has unexpected side-effects. The development of global positioning systems (GPS), initially in secret for the military but later openly aimed at a large group of prospective buyers, has resulted in the availability of relatively cheap gadgets that accurately determine locations at the Earth's surface. When applied on harvesters that are also equipped with sensors for continuous yield monitoring ('yield monitoring on-the-go'), some interesting results have been obtained (Cahn *et al.*, 1984). Differences in crop production within agricultural fields, which are the management units for a farmer, turned out to be much higher than anticipated. They often ranged from a factor of two to four. These results are new. Farmers know, of course, that differences occur, but such knowledge is hard to quantify because documentation by making a series of small harvests within a field is not feasible from a management point of view. Yields are therefore always expressed in terms of tons per hectare. This is determined by dividing total yields by the total area of the farm being covered by a particular crop, and ignoring local differences. Application of GPS and yield-sensing equipment does, however, allow expression of such differences.

What are the implications of knowing yield differences within fields? The first challenge is to find the reasons why these differences occur and the second challenge is to develop management procedures that can reduce the differences. The overall expectation is that reducing differences would be economically attractive for the farmer and ecologically attractive for the farmer and for society. Even though such expectations appear reasonable, specific research is needed to prove the point.

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

Research, as discussed here, has been in progress in several countries with a clear focus on soil fertility. The traditional method of collecting soil fertility samples is to obtain a mixed sample from a field and then deriving a corresponding fertilizer recommendation by using standard tables relating fertilization rate to yield. This procedure underestimates rates for some areas and overestimates them for others. The over-fertilization leads to leaching below the root-zone and possible groundwater pollution, whereas under-fertilization leads to inefficient fertilizer use and suboptimal production conditions. Several studies have been reported in which separate samples were taken and fertilization rates were determined for each point (Franzen & Peck, 1994). Using information technology, such as GIS and computer-guided application devices, helped achieve soil- or site-specific management. Varying the applied amount of fertilizer within a field based on site-specific fertility analysis, saves money (from $10 to $80 per acre on average) and reduces leaching of excess fertilizer beyond the root-zone.

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

This paper addresses the question of which soil-related research is necessary to allow execution of precision agriculture, and how the research should proceed. Some first results of an exploratory, ongoing study being carried out in the Netherlands are presented.

SOIL RESEARCH FOR PRECISION AGRICULTURE

The following elements may be distinguished when defining soil research for precision agriculture in specific fields:

(1) Establish a soil database that contains relevant soil characteristics.
(2) Monitor crop growth and physical and chemical conditions during one or more growing seasons. Use data in expert systems to calibrate and validate simulation models for crop growth and solute fluxes.
(3) Define threshold values for yields and chemical fluxes from an economic and environmental point of view and determine when they are exceeded under different well-defined forms of management and variable weather conditions.
(4) Use modeling techniques to define management schemes that avoid exceeding threshold values while maintaining yields at economical levels.
(5) Implement the schemes by developing and using site-specific technology.
(6) Develop operational decision support systems to be used in practice.

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

SOIL DATABASE

The Van Bemmelenhoeve farm in Wieringermeer, The Netherlands (Fig. 1), was studied. Particular attention was paid to a 300 by 200 m field, shown in Fig. 2. An exploratory soil survey was made and soils were

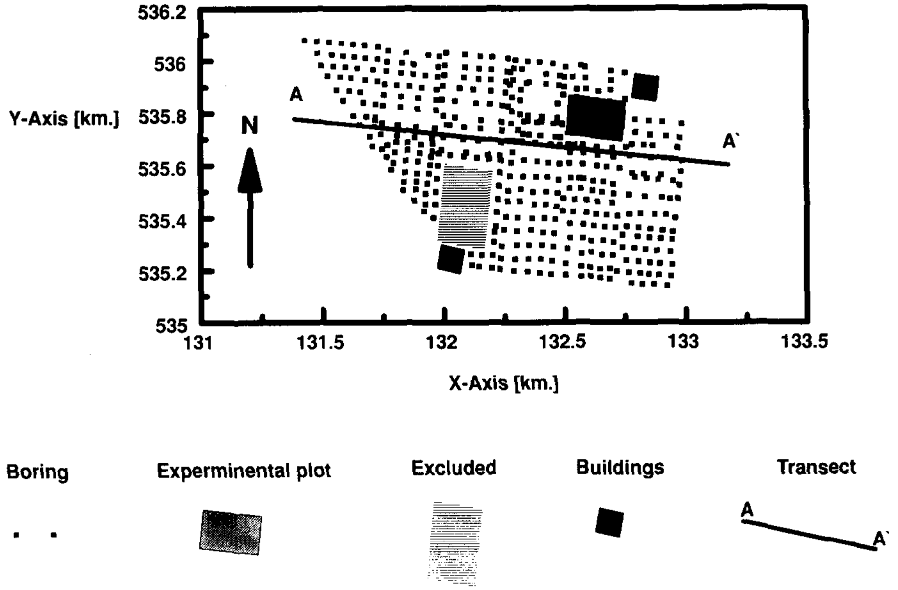

Fig. 1. Layout of the experimental farm 'Prof. van Bemmelenhoeve', Wieringermeer, The Netherlands.

classified as Typic Udifluvent (Soil Survey Staff, 1975). A geostatistical analysis indicated that the observed spatial variability could be optimally characterized by using a 50 m by 50 m grid, which resulted in 30 detailed point observations of soil characteristics such as texture and organic

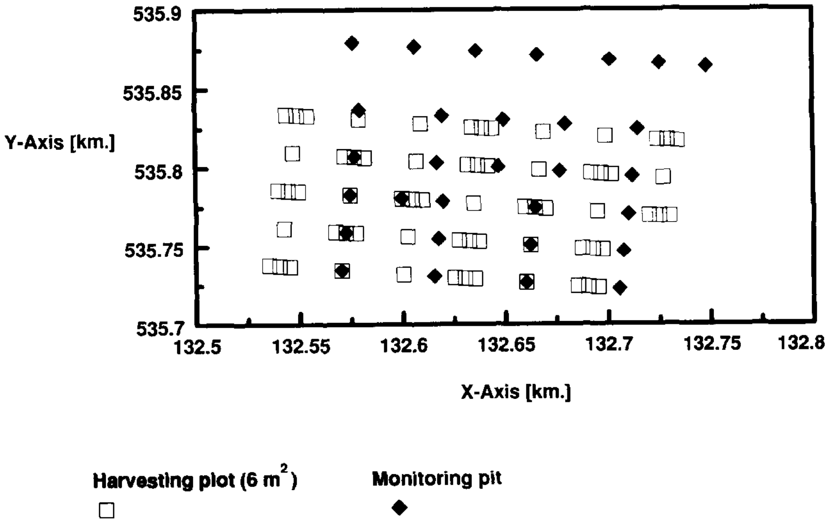

Fig. 2. Layout of the experimental plot with harvesting and monitoring pits.

TABLE 1

Description of the Functional Layers and Corresponding Van Genuchten Parameters for the Hydraulic Functions

Layer	ρ (kg/dm^3)	*sd*	*Organic matter* %	*Clay* %	K_{sat} (cm/day)	θ_{sat}	*sd*	θ_{res}	α	n	l
F1	1·48	0·039	0–2	0–4	183	0·40	0·02	0	0·03096	2	2·2842
F2	1·21	0·097	0–2	4–11	128	0·53	0·03	0·05	0·02000	1·5	0·5
F3	1·15	0·231	0–2	11–23	7	0·57	0·05	0·05	0·18650	1·2676	0·4205
F4	1·30	0·045	0–3	4–23	335	0·52	0·02	0·02	0·24986	1·2154	1·0791

matter content. Each observation was geo-referenced. In contrast to a traditional soil survey, attention was focused here on functional soil horizons and not on the traditional genetic horizons. Functional horizons consist of combinations of genetic horizons with identical behavior. Here, physical properties are used to distinguish functional horizons (Finke, 1993). In this field, soils were strongly layered and distinction of functional layers was based on descriptions of soil texture, as observed during augering, and a preliminary classification that was finalized after

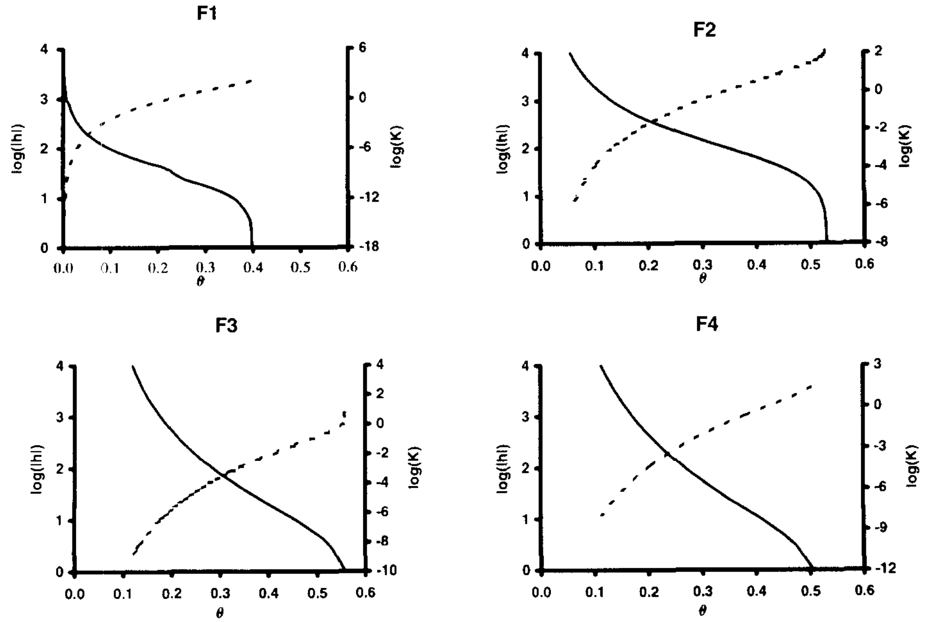

Fig. 3. Average moisture retention and hydraulic conductivity data for the four functional layers. Averages are based on five replicate measurements.

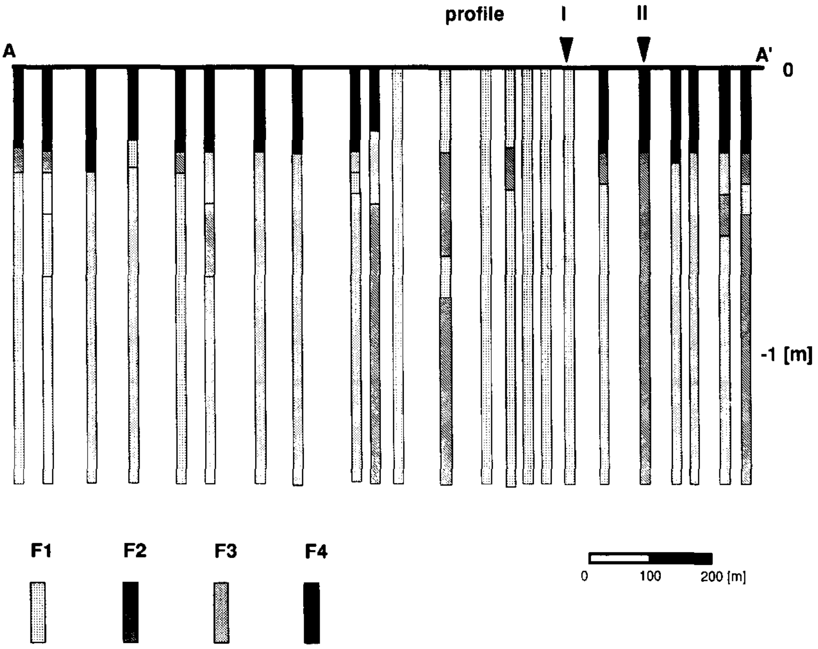

Fig. 4. Cross-section of soil profiles along the line A–A' in Fig. 1. Each profile is composed of a number of functional layers.

measurement of hydraulic conductivity and moisture retention data, using modern techniques (Finke, 1993). Four functional horizons were distinguished, as summarized in Table 1, which also lists the van Genuchten coefficients for the measured hydraulic characteristics. Average measured hydraulic conductivity and moisture retention data of each of the four layers are shown in Fig. 3. Use of functional horizons is attractive because the vertical sequence of layers at each point observation can be represented by only a few, and sometimes only one, functional horizon, rather than a relatively high number of pedological horizons. A representative cross-section through the field of study, in which each depth is characterized by a functional layer is shown in Fig. 4. Basic hydraulic soil data can be used for simulation modeling for each point, and will be discussed later.

Geo-referenced soil data, as collected here, are quite different from data derived from conventional, highly detailed soil maps. Soil maps define mapping units in which a particular soil type is assumed to occur. Attention in this study, however, is on defining point data in terms of characteristics that are relevant for modeling. Expressions for areas of land are obtained by interpolation of point data (Finke, 1993).

CROP GROWTH AND SOIL CONDITIONS: EXPERT SYSTEMS AND MODELS

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

Advisory schemes are suitable for exploring the expected effects of site-specific management. In the field being investigated, 30 soil fertility samples were taken. Also a composite sample was made. Each sample was interpreted in terms of fertilization rate and expected yield. Results are summarized in Fig. 5, which shows total N as measured on 8 June. The map was obtained by interpolation, using the kriging technique, of 30 data points. Using computer simulation models for crop growth and

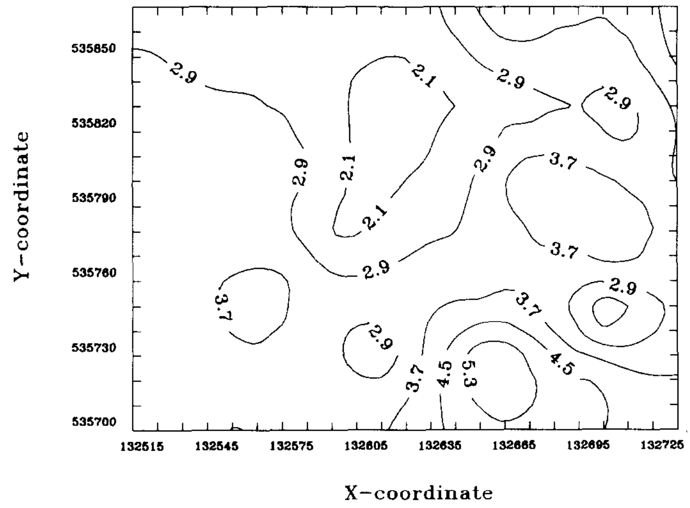

Fig. 5. Total N (10^2 kg / ha) at 8 June, for a depth of 0–60 cm below the surface.

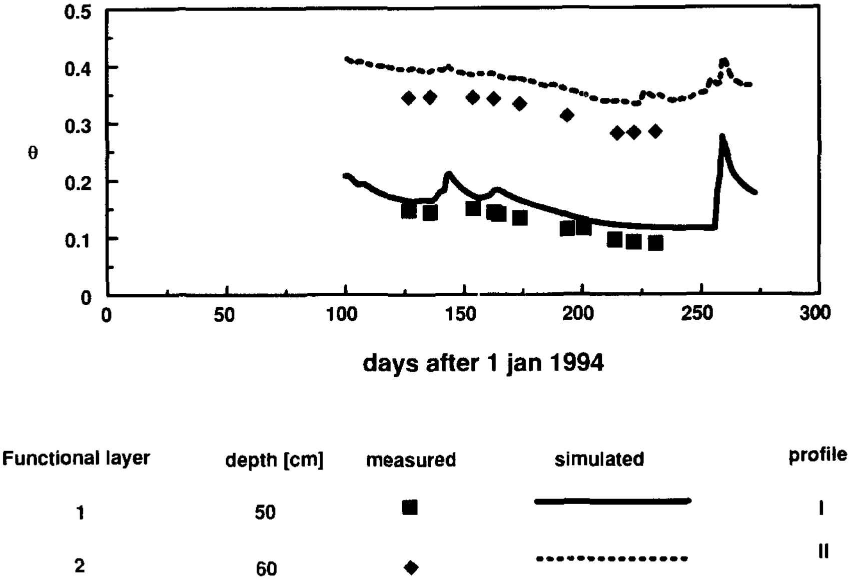

Fig. 6. Simulated versus measured soil moisture content for sandy (I) and loamy (II) soil profiles (for locations, see Fig. 4).

solute fluxes represents a modern and more detailed method of expressing relations between crop growth and soil conditions (Teng & Penning de Vries, 1992). Models can be used to express crop growth and environmental effects. Different types of models can be distinguished. In our work, use is made of the WAVE model for simulating water movement,

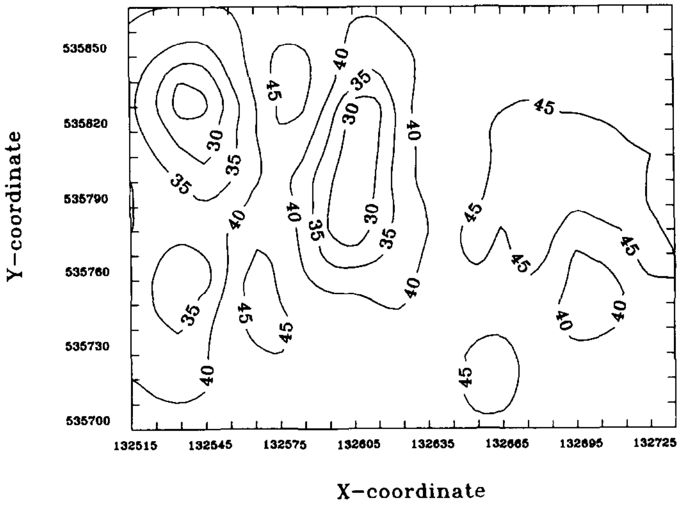

Fig. 7 (a)

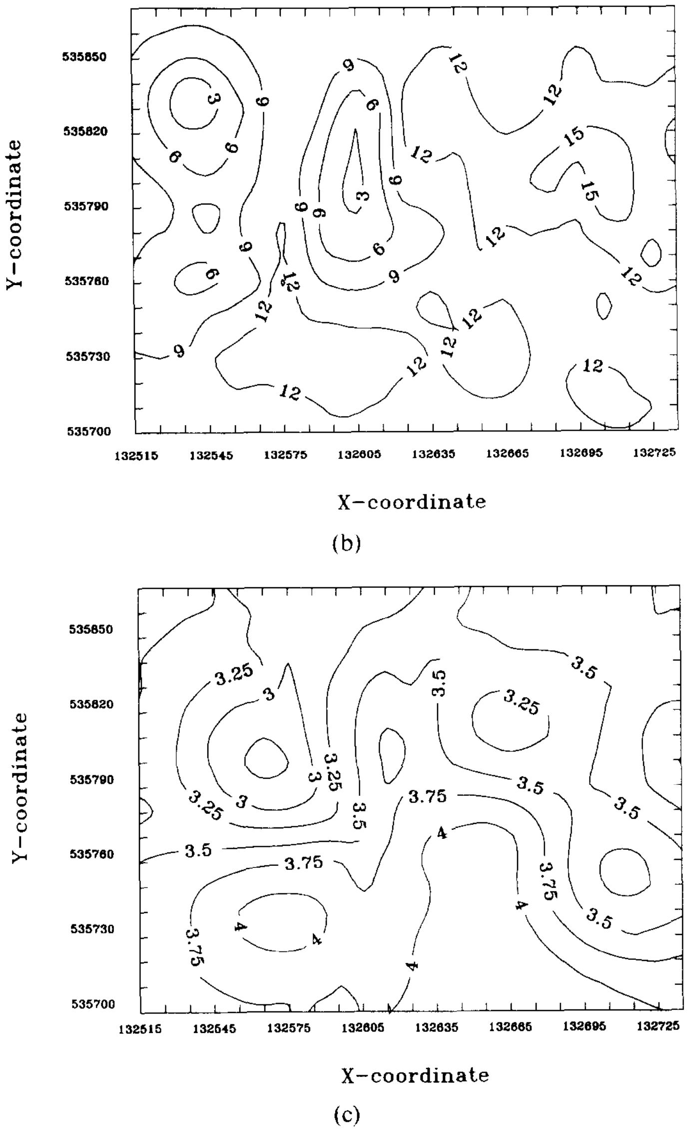

Fig. 7. (a) Total potato yield (ton/ha) in 1994. (b) Yield (ton/ha) for tubers with diameter larger than 50 mm. (c) Leaf area indexes (LAI) measured on 3 August 1994. Patterns were obtained by interpolating 80 point measurements.

nitrogen transformations and crop growth. This model was developed in the context of an international program financed by the European Union. The model was run for the observation points in the study field. Calibration and validation was based on measured and calculated water contents in the soil during the 1994 growing season. A representative example is shown in Fig. 6 for a relatively sandy and a clayey spot. The two locations are shown in Figs 2 and 4. In this study potato yields were measured by harvesting 65 small plots. These values were interpolated and the results are shown in Fig. 7(a). Yields vary between 30 and 45 tons/ha, which represents a significant range. More important than total yield is the yield of potatoes with a diameter of more than 50 mm (Fig. 7b). These potatoes are marketable for chips. Differences are pronounced, and range from 3 to 15 tons/ha. The smallest values are obtained in the areas with the lowest yields. For example, total yields of 30 tons/ha correspond with yields of large potatoes of 3 tons/ha (10%), while total yields of 45 tons/ha correspond with yields of large potatoes of 12–15 tons/ha (30%). Here, yields were measured, but they can also be simulated. However, measurements are always preferred, if feasible, in view of the uncertainties associated with modeling. In this context, Fig. 7(c) shows measured leaf-area indexes, obtained with a hand-held crop-scanning apparatus. In general terms, patterns of leaf-area indexes measured on 3 August correspond reasonably well with the yield patterns measured in September. In all these examples, point data were interpolated to areas of land by using geostatistical techniques (Finke, 1993). The WAVE model was used to calculate water and nitrate fluxes for the 1994 growing season. Some selected results are shown in Figs 8 and 9 using again the two contrasting point locations that were illustrated in Figs 2 and 4. The figures show nitrate profiles as a function of time and demonstrate clearly that penetration of nitrates proceeds quicker and to a relatively greater depth in the more sandy soil. The model was used

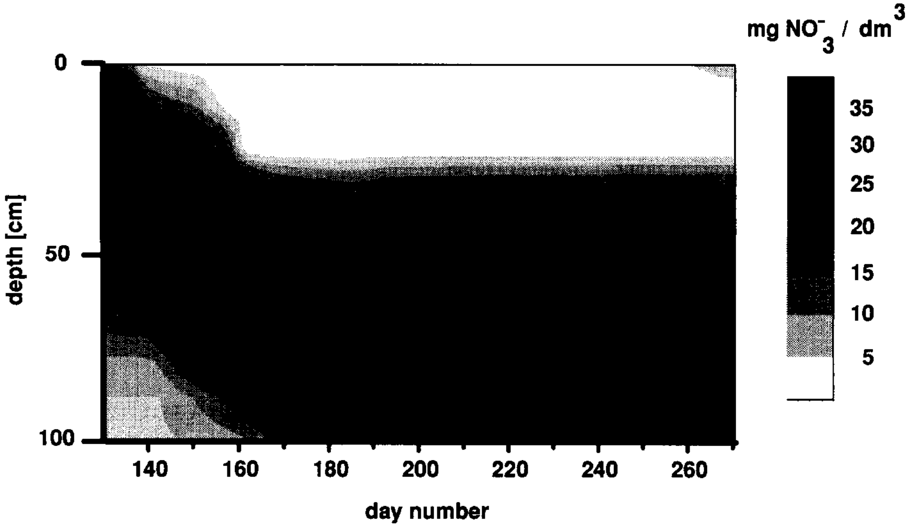

Fig. 8. Simulated nitrate profile during the growing season in a sandy soil (I).

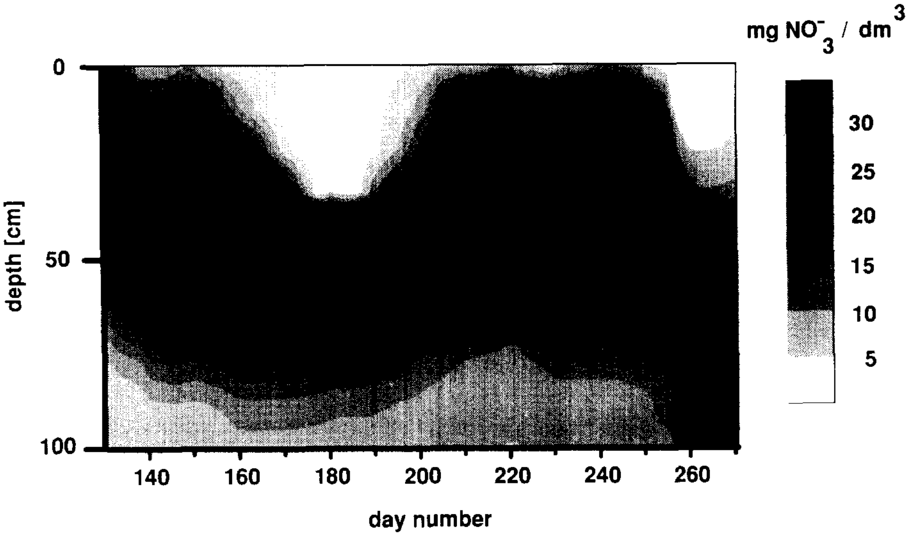

Fig. 9. Simulated nitrate profile during the growing season in a loamy soil (II).

here for real time conditions, allowing comparisons with measured data. Of course, using simulation models is particularly attractive when making runs for weather and soil conditions in different years.

EXCEEDANCE OF THRESHOLD VALUES OF SELECTED INDICATORS

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

To judge the level of crop growth and environmental side-effects we need indicators, and their threshold values are needed as a reference. Indicators are defined as environmental statistics that measure or reflect environmental status or change in condition, while threshold values represent levels of environmental indicators beyond which a system undergoes significant change, i.e. points at which stimuli provoke significant response (FAO, 1993). For our study, soil water content and nitrate fluxes in the soil are two obvious indicator values. Both are shown in Figs 8 and 9, and demonstrate, in principle, the importance of using simulation models when dealing with the operationalization of the indicator and threshold value concept. Here, we see a direct application of ICASA software in the future. Without the models, there would not be enough time or funding to generate the large number of data needed to test and implement the concept. Implementation gives rise to a number of questions. Which indicators relate to crop production and which to environmental aspects? What are the threshold values for these indicators? How feasible is it to have not only common indicators but common threshold values as well for the soil functions being considered? For our example, we will consider soil water content and nitrogen content as indicators. Both are important for crop growth and environmental conditions.

The dry months of July and August reduced crop growth considerably. The model calculates potential versus actual transpiration (Fig. 10 shows potential versus actual transpiration for two arbitrarily chosen points in the study field). Data presented in Fig. 10 can also be used to show how much water should have been applied at what time to allow potential transpiration to occur. The nitrogen content is more difficult to characterize. Crop demand is a function of the growth stage; downward fluxes of nitrate are a function of the amount of N in the root-zone and the water content, which is directly associated with the flux. Simulated downward nitrate fluxes can be derived from data shown in Figs 8 and 9. They can be interpreted directly in terms of exceedance of a critical threshold value for leaching by drawing a horizontal line at the threshold level and by counting the number of days the nitrate concentration in the percolating soil water was higher than a selected critical threshold of, say, 50 mg/liter. At the same time, N needs of the crop can be determined for

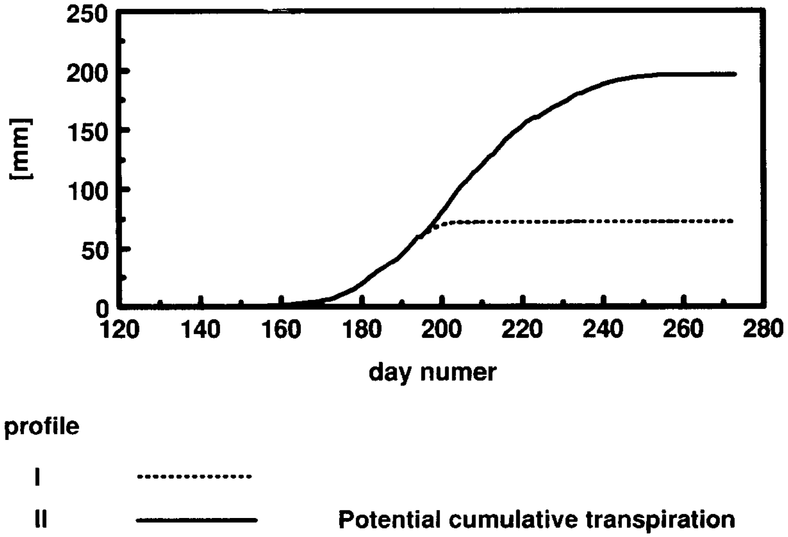

Fig. 10. Simulated cummulative transpiration for a potato crop at two locations.

any period in the growing season when aiming for nutrient unlimited yield. This determination represents a more sophisticated approach to the problem of determining relations between nutrient status, fertilization and yield as discussed earlier. Clearly, in defining an optimal system, requirements defined for production must be balanced against requirements for environmental quality.

BALANCING YIELDS AND SOLUTE FLUXES

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

So far, only real weather conditions in the 1994 growing season have been considered. Conditions are different in different years and models can be used to characterize such conditions. This will be done as the study progresses.

IMPLEMENTATION BY SITE-SPECIFIC TECHNOLOGY

Once point data are obtained with the procedures described in the previous section, we have to consider spatial differences. As stated above, these can be derived from point data by interpolation techniques (see Fig. 7a–c). Next, technical means have to be defined to use those differences with the purpose of obtaining a better production system from a balanced ecological point of view. No new original research results will be presented here, but work elsewhere will be briefly reviewed. Interesting developments occur in the USA, UK and Germany in terms of the development of site-specific technology, including GPS guided fertilization machinery (Murphy *et al.*, 1994; Robert *et al.*, 1994). Machines need to be fed with proper spatial data and this still presents a major challenge to research.

OPERATIONAL DECISION SUPPORT SYSTEMS

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

CONCLUSIONS

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

(2) Differences in yield can be due to many factors, which were explored in this study. Computer simulation techniques were used successfully to demonstrate the importance of the water supply capacity in governing yield. In addition, simulation allowed an estimate of nitrate fluxes in the soil which govern environmental side-effects of the production system. Simulation techniques are important as exploratory tools in

finding an acceptable balance between production and environmental pollution. ICASA software is very applicable in this context.

(3) A new type of soil survey was discussed which allows distinction of so-called functional layers, to be characterized in terms of field properties such as texture, with typical hydraulic characteristics. The highly complex stratified marine soils of this study could be represented successfully by only four functional horizons.

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

ACKNOWLEDGEMENTS

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