# QUANTIFYING DIFFERENCES IN SOIL STRUCTURE INDUCED BY FARM MANAGEMENT

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# QUANTIFYING DIFFERENCES IN SOIL STRUCTURE INDUCED BY FARM MANAGEMENT

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# STELLINGEN

1. De definitie van de bodemstructuur van een bodemtype moet gebaseerd zijn op de range van mogelijke bodemstructuren in plaats van op één representatieve bodemstructuur. Gebruik maken van de relatie tussen bodemmanagement en bodemstructuur maakt een dergelijke inventarisatie mogelijk.

   Bouma, J. 1994. Sustainable land use as a future focus for pedology. Soil Sci. Soc. Am. J. 58: 645-646.

   Dit proefschrift

2. Naast de hoeveelheid "beschikbaar" water voor de plant speelt de "toegankelijkheid" van dit water een belangrijke rol in gestructureerde bodems.

   Dit proefschrift

3. Drempelwaarden voor uitspoeling zijn zinloos indien de tijdschaal, waarover de betreffende drempelwaarde beschouwd moet worden, ongedefinieerd is.

   Dit proefschrift

4. Variatie in jaarlijkse weersomstandigheden maakt landevaluaties, gebaseerd op slechts enkele jaren van veldexperimenten, onbruikbaar.

   Dit proefschrift

5. Een ecologisch geteeld produkt betekent niet automatisch een duurzaam geteeld produkt.

   Reganold, J.P. 1995. Soil quality and profitability of biodynamic and conventional systems: a review. Amer. J. Alternative Agric. 10: 36-45.

6. Bodemclassificatie is een middel en geen doel op zich.

7. Het economisch belang van de Nederlandse landbouw wordt vaak sterk overschat.

8. Bij de voorspelde gewapende conflicten betreffende de verdeling van het schaarse water zal het water slechts functioneren als de spreekwoordelijke stok om een hond mee te slaan.

9. Voor elk natuurgebied in Nederland moet worden aangegeven welk historisch cultuurlandschap wordt nagestreefd.

10. Een duidelijk onderscheid tussen 'gelijkheid' en 'gelijkwaardigheid' maakt veel principiële discussies helderder.

11. Om de langlopende procedures voor asielzoekers werkelijk te bekorten, zouden asielzoekers die langer dan een jaar op een beslissing omtrent hun status wachten, direct in aanmerking moeten komen voor een verblijfsvergunning.

12. Het territoriumgedrag van natuurbeschermers staat een natuurbeleving, voor mens én dier, in de weg.

13. De vermeende problemen van het AIO/OIO stelsel hebben vaak meer te maken met algemene problemen die zich voordoen bij het uitoefenen van een eerste baan, dan met het stelsel zelf.

14. De borden met het opschrift "fietsen buiten de rekken worden verwijderd" bij overvolle fietsenrekken van NS stations, geven aan waar de prioriteit van het vervoerbeleid in Nederland niet ligt.

15. Het feit dat computers het schaakspel beter beheersen dan de mens, toont juist het intellect van de mens aan.

Stellingen behorend bij het proefschrift van P. Droogers *Quantifying differences in soil structure induced by farm management*, Wageningen, 16 september 1997.

# Voorwoord

Het werken aan dit proefschrift heeft mij de afgelopen vier jaar over het algemeen veel voldoening gegeven. Hoewel het schrijven van gemiddeld 45 woorden per dag niet veel lijkt, heeft dit toch de nodige inspanning gevergd. Deze inspanning en het plezier om aan dit proefschrift te werken, is mede te danken aan diverse mensen die hierbij, direct of indirect, betrokken zijn geweest.

Johan Bouma heeft als promotor en directe begeleider in hoge mate bijgedragen tot het tot stand komen van dit proefschrift. Altijd weer wist hij nuttige ideëen te genereren om het onderzoek in de juiste richting te sturen. Concept artikelen werden door hem altijd binnen twee dagen, weekenden niet uitgezonderd, van zeer steekhoudend commentaar voorzien. Naast het genereren van ideëen en het becommentariseren van artikelen, heeft zijn stimulerende persoonlijkheid mij zeer goed geholpen. Johan, bedankt.

Een groep van vijf mensen, "mijn" afstudeervakkers, hebben ook een wezenlijke bijdrage geleverd aan dit proefschrift en aan het plezier om eraan te werken. Jorunn Fleumer heeft de opstartproblemen van het onderzoek aan den lijve ondervonden. Hoe vaak hebben we niet gedacht dat alle 'bugs' uit WAVE waren verdwenen? Anneke Fermont heeft nauwgezet het onderdeel berijdbaarheid en bewerkbaarheid uitgewerkt. Bauke van der Meer heeft vol overgave meegewerkt aan het verhaal over de toegankelijkheid van water voor wortels. Geuch de Boer heeft macroporiën geanalyseerd waarbij veel veldwerk gecombineerd werd met een zware computer-analyse. Tenslotte heeft Erik Meyles het onderzoek in een breder kader gezet met nadruk op de organische stof. Jorunn, Anneke, Bauke, Geuch en Erik bedankt voor jullie inspanningen en het plezierig samenwerken.

Piet Peters heeft de bodemfysische bepalingen verricht en veel ondersteuning gedurende het veldwerk gegeven. Daarnaast was het reizen naar en verblijven in Zeeland met Piet altijd weer plezierig en zullen de lokale kroegen ons missen. Binnen de sectie bodemkunde en geologie zijn nog diverse andere mensen betrokken geweest gedurende bepaalde perioden: Jan Verhagen als meest betrokken collega, Alfred Stein bij statistische problemen en als mede-auteur, Harry Booltink als bodemfysisch- en modellen-expert, Rienk Miedema tijdens de opstartperiode, Paul Verburg bij de respiratie metingen, Eef Velthorst voor de chemisch analyses en natuurlijke mijn kamergenoten Roel Plant en Leo Tebbens.

Verder ben ik dank verschuldigd aan een aantal boeren in Zeeland die altijd toestemming gaven om te graven, boren, meten en hun land te berijden. Met name Albert Ebbens van de Rusthoeve, Maarten Guepin van Ter Linde en familie De Visser bedank ik voor hun belangeloze medewerking en informatie verstrekking.

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PETER

*Wageningen, juli 1997.*

# CONTENTS

# GENERAL INTRODUCTION

Expanding populations and economic development have placed pressure upon soil, water and plant resources in both developing and developed parts of the world. Sustainable land management practices have become therefore an increasing matter of concern in recent years (Pieri et al., 1995). It is widely accepted that current agricultural practices have many detrimental effects and cannot be regarded as sustainable (Rabbinge, 1997). On the one hand, this unsustainability is based on poverty. People in developing countries often have no means to invest in measures to prevent degradation of natural resources. They cannot afford to purchase inputs to use land efficiently, resulting in a considerable amount of new land, often less suitable for agriculture, being brought under production. On the other hand, riches can impede sustainability as well. Exclusive consideration for high productivity has encouraged an excessive use of inputs like machinery, fertilisers, pesticides, combined with mono-cropping at a large scale. Leaching of agro-chemicals, loss of biological diversity and soil structure deterioration are examples of the negative effects of these high-input production systems (FAO, 1991).

## *Sustainability*

Many definitions have been proposed, and are likely to be proposed in future, for sustainability and sustainable land use, ranging from very broad and generalised towards more restricted and detailed. Peskin (1994) extracted from literature three categories of definitions for sustainability: sustaining the environment, sustaining the economy and sustaining either the environment or the economy subject to the other. For example, FAO (1991) stated that agriculture was basically a sustainable process "as long as renewable resources are used at a rate compatible with their natural regeneration". This restrictive definition is not realistic as food must be produced for approximately 5.5 billion peoples nowadays, a figure which will at least have doubled in the next century (Opschoor, 1994). Therefore, a modified definition, with four criteria was formulated starting with "meeting the basic nutritional requirements of present and future generations, qualitatively and quantitatively" (FAO, 1991). The entire definition covered two full pages of text!

From the large amount of definitions the one proposed by FAO (1993) was followed here, as it combines completeness and compactness:

> "Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously:
>
> - maintain or enhance production and services (productivity)
> - reduce the level of production risk (security)
> - protect the potential of natural resources and prevent degradation of soil and water quality (protection)
> - be economically viable (viability)
> - and socially acceptable (acceptability)."

The question arises whether or not sustainability can be achieved considering the growing world population. Two groups of studies can be distinguished: the optimistic versus the pessimistic scenarios (FAO, 1991). Optimistic scenarios are based on the concept of potential productivity and argue that the gap between potential and actual productivity is very large. Transferring existing knowledge and technologies to areas that are far below their potential productivity will be the solution for sustainability. Other studies emphasise that current development patterns are not sustainable and conclude from extrapolating current trends in population, land availability and food production that a "nightmare scenario" is likely (FAO, 1991). This can also be expressed as "weak" and "strong" sustainability. The "weak" sustainability approach considers natural resources and economy as substitutes, while the "strong" sustainability approach considers natural resources and economy to be complementary (Duijnhouwer et al., 1994).

### Sustainability indicators

Definitions of sustainability are mainly conceptual and not focused on practical applications. Therefore, attempts have been made to translate sustainability into indicators to assess, monitor and evaluate the quality of land resources in a quantitative way. One of the first indicators to quantify sustainability was the *Land Quality*, defined as "a complex attribute of land which affects its suitability for specific use in a distinct way" (FAO, 1976). Recently, a renewed interest in defining sustainability indicators can be observed in literature. FAO (1993) proposed a strategic Framework approach for Evaluating Sustainable Land Management (FESLM), based on the original Land Evaluation Framework. They defined *Indicators* as "environmental statistics that measure or reflect environmental status or change in condition".

Pieri et al. (1995) indicated that economic and social indicators are already in regular use, but only few are developed to assess land qualities. They defined *Land Quality Indicators* as: "measures that describe land quality and human actions which relate to it". These indicators convey the most significant information in summary form and can be subdivided into: "descriptive indicators" and "performance indicators". Examples of *Land Quality Indicators*, some of them somewhat remarkable for soil scientists, are given: crop yield, nutrient balance, maintenance of soil cover, soil quality, soil quantity, water quality and water quantity (Pierie et al., 1995). A discussion paper, describing a theoretical framework for land evaluation, concentrating on how *Land Qualities* (according to the FAO 1976 definition) should be expressed in time and space, was presented by Rossiter (1996).

Meanwhile, the Soil Science Society of America developed a system for evaluating soils using the terms *Soil Quality* and *Soil Quality Indicator* (Karlen et al., 1997). The simplest definition for *Soil Quality* is "the capacity of a soil to function". An expanded version was proposed as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". An example of a *Soil Quality Indicator*, considering production, environment and risk, was proposed by Bouma and Droogers (1997). This indicator resulted directly from the studies reported in this thesis. Regardless of the applied indicator, selecting and considering the appropriate space, time and knowledge-level is essential. Establishing research chains, representing the sequences of activities based on these three characteristics, is necessary for a clear analysis of the problem to be studied (Bouma, 1997).

### Soil survey

Traditionally, activities of soil survey were focused on production of soil maps and soil classification systems. However, in many countries soil survey has nearly completed its task and pessimistic views have been expressed about its future (Zinck, 1995). On the other hand, this can be seen as a challenge to use soil survey expertise to focus on answering current questions about sustainability, as was already argued by Bouma (1988). Moreover, Dumanski (1995) advocated that soil survey should change their focus towards a more problem-oriented approach, instead of traditional, systematic data collection practices. Keywords should be "flexibility" and "diversity" in order to deal with actual topics like land evaluation, soil conservation, soil quality monitoring and sustainable land management. Van der Pouw (1995) described a very optimistic view for the Dutch soil survey, in which a combined use of existing knowledge and new scientific and technological methods can be used to answer questions posed by society. A link of soil survey with land management is proposed by all these authors.

### Management

For a long time, farm management was focused on only one objective: the production of an adequate amount of food. About two decades ago, this objective was reached in Western countries and now a surplus of food is being produced. At the same time, an increasing concern on environmental issues arose. These two aspects have initiated the development of new farm management practices, with keywords like organic, biodynamic, ecological, no-till and minimum-till (Reganold, 1995). These definitions are mainly related to the decisions taken at the strategic level. However, tactical and operational aspects can cause differences within management types defined at the strategic level. A farm referred as "organic" or "biodynamic", for example, does not explicitly mean that it is sustainable (Reganold, 1995).

It is logical to concentrate on soils when evaluating and comparing the effects of different management practices as these effects are expressed by soil features that can be observed and measured. Especially soil structure and the organic matter content are important aspects as they reflect management practices at an integrated level (Kay, 1990). Bouma et al. (1993) argued the importance to include this farm management in sustainability studies rather than only focusing at a regional level.

### Soil structure

Soil structure is defined here as: "The physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves" (Brewer, 1964). As stated before, differences in soils originate not only from their genesis and their natural soil-forming processes, but also from the applied management. It is therefore likely that each soil series has a range of soil structures associated with particular management practices. Each soil structure will have its own characteristic properties, which leads to the conclusion that each soil series has a characteristic range of properties as expressed as different soil structures for land use. This range can be defined as "windows of opportunity" (Bouma, 1994).

Differences in soil structures can be expressed in a qualitative way by describing the morphological features of soil profiles, or using thin sections for detailed analysis. Measurements, in field or laboratory on disturbed or undisturbed samples, provide quantitative data on soil structure. Many, well tested, techniques are available nowadays (e.g. Klute, 1986a and Page et al., 1982). Quantitative data give the opportunity to use simulation models to assess sustainability indicators based on practical applications. In this thesis, emphasis was put on parameters related to soil-water-crop dynamics, nitrogen and organic matter dynamics. Hydraulic characteristics, retention and conductivity data, describe the macro- as well as micro-soil structure in a concise way, with practical applications for plant growth and leaching potential. Nitrogen dynamics is used here because it is an important factor for crop growth, but also because it can result in pollution of groundwater and, consequently, our drinking water. Finally, organic matter can be considered as an integrating soil parameter, reflecting management practices over periods of decades.

## Methodology

Effects of different management types are often analysed by using experimental plots on experimental farms. A field is divided into small plots and a random selection procedure, considering replicates, determines the treatment for the different plots. After a certain time, effects of the applied management are determined and conclusions can be deduced. Although useful information has been obtained from such experiments, they have some serious drawbacks. First of all, conditions of small experimental plots are different from real field situations. Second, experiments are influenced by unpredictable weather conditions. Results of experimental plots are often characterised by statements like "weather conditions during the experiments were extremely dry/wet/sunny/cloudy". Third, effects of management can take decades before they are in an equilibrium state (Phillips and Phillips, 1984). Finally, agriculture changes in ways that cannot be foreseen, making carefully designed long-term experiments obsolete within one or two decades (Jenkinson, 1991).

A methodology based on two central themes can avoid these problems: (i) making use of different management practices as performed by "normal" farmers and (ii) applying well-tested simulation models for soil, water, plant and nutrients dynamics. Bouma (1969) compared soil structures of two farms on a similar soil type and concluded that management had a strong effect on soil structure. Also Kooistra et al. (1985) studied the effect of different farm management practices on soil structure, which was combined with simulation modelling (Van Lanen et al., 1992) to assess the sustainability of the different systems. Also this approach has some weak points, which, however, can be diminished by a careful consideration of these weak points. First of all, only management types which exist already can be analysed, but field visits and discussions with farmers will lead to a surprisingly number of management practices. Second, natural heterogeneity between fields will be bigger than heterogeneity of experimental plots within one field. But variation within one field should not be underestimated (e.g. Verhagen, 1997). Characterising natural variation in and between selected fields can resolve this problem. Finally, simulation models are simplifications of the real world, which may lead to errors as well. However, using well tested and validated simulation models can diminish this problem.

## Outline of the thesis

In Part I a comparison is made between conventional and biodynamic farm management using soil structure differences induced by farm management combined with simulation models. Potential productivity as well as workability and trafficability was used to express differences between the two systems in quantitative terms.

Part II describes processes which have to be considered during the evaluation of soil structure differences as a result of different management practices. First, chapter 3 describes the effects of using a representative soil profile vs. individual profiles and the effect of variation in weather conditions on transpiration ratios. Time aggregations over which critical values of nitrogen leaching should be considered are explored thereafter. As macro-porosity might have a significant influence on water and solute dynamics, an extensive analysis has been performed to relate macro-porosity with management, emphasising appropriate parameters to describe this macro-porosity. Part II finishes with a chapter related to water accessibility to plant roots. Again, soil structure types formed by different farm management practices were used, in combination with a methodology based on measurements and simulation modelling.

Implications for future soil science, especially soil survey, are described in Part III. Chapter 7 describes how existing soil survey information can be used to define indicators for sustainable land management, and chapter 8 concentrates on implications for future soil survey methodology. Finally, general conclusions deduced from the different parts of this study are presented.

# PART I

# Comparing biodynamic and conventional management

Chapter 1

Droogers, P., and J. Bouma. 1996. **Biodynamic versus conventional farming effects on soil structure expressed by simulated potential productivity.** Soil Sci. Soc. Am. J. 60: 1552-1558.

Chapter 2

Droogers, P., A. Fermont, and J. Bouma. 1996. **Effects of ecological soil management on workability and trafficability of a loamy soil in the Netherlands.** Geoderma 73: 131-145.

# Chapter 1

# BIODYNAMIC VERSUS CONVENTIONAL FARMING EFFECTS ON SOIL STRUCTURE EXPRESSED BY SIMULATED POTENTIAL PRODUCTIVITY

**Abstract** Effects of alternative farming systems on soil structure need to be quantified to judge the sustainability of the systems. This study was conducted to compare two farming systems by converting "static" basic soil properties into a "dynamic" assessment using simulation modeling. Increasingly popular biodynamic farming systems use no commercial fertilizers and pesticides but apply organic manure and compost. Soil conditions on four fields on two farms where biodynamic and conventional soil management had been practiced for about 70 years were investigated with morphological and physical methods. Soils (loamy, mixed, mesic Typic Fluvaquents) were pedologically identical. Four procedures were used to express differences in soil structure as a function of different management: (i) morphological description; (ii) measurement of basic and static soil parameters such as bulk density, organic matter, and porosity; (iii) measurement of soil hydraulic characteristics; and (iv) determination simulated water-limited yields. The latter procedure provides a criterion that is quantitative, is directly related to a practical aspect of soil behavior, and reflects the highly nonlinear soil-water processes. The WAVE simulation model was used to predict water-limited potato (*Solanum tuberosum* L.) yields with climatic data of 30 years. Basic static soil parameters were not significantly different but simulated yields were significantly different and were 10 200 and 10 300 vs. 9400 and 9700 kg dry matter tuber yield $ha^{-1}$ $yr^{-1}$ for the biodynamic and the conventional fields, respectively. Simulation modeling of crop yields thus provides a relevant expression for the production potential of the two different farming systems.

## INTRODUCTION

Conventional farming systems have evolved with a primary emphasis on high yield and quality of crop production, and secondary considerations for the condition of the soil. Sustainable farming systems are being developed to help modern agriculture solve important problems in soil productivity, such as erosion, leaching, or runoff, and to ensure long-term crop production. One of the alternative production systems that is increasingly popular is biodynamic farming (Reganold, 1995). Like organic farming, biodynamic farming uses no synthetic chemical fertilizers and pesticides, and instead emphasizes use of compost and animal and green manure, control of pests by natural means, use of crop rotation, and diversification of crops and livestock. The major difference with organic farming is that biodynamic farmers add specific amendments to their soils, crops, and composts to enhance soil and crop quality and to stimulate the composting process (Koepf et al., 1976). Reganold (1995) reported that only a few studies examining biodynamic methods or comparing biodynamic farming with other farming systems have been published. These publications have shown that the biodynamic farming systems generally have better soil quality, lower crop yields, and equal or higher net returns per hectare than their conventional counterparts. Complication in comparative studies is that they cannot be based on systems that are only a few years old, but should be based on systems that have existed for decades (Phillips and Phillips, 1984), thus excluding most short-duration research work based on experimental plots. This problem was avoided in this study by focusing on farms where a given type of management had been applied for about 70 years.

Biodynamic farming emphasizes the importance of natural biological, physical, and chemical soil processes to create favorable circumstances for plant production. Soil structure provides an integrative expression of the effects of these processes and can, therefore, be a useful focal point for a comparative study on soils in conventional and biodynamic farming systems (Elliott and Coleman, 1988). Soil structures can be compared in a descriptive, qualitative manner, but a dynamic, quantitative approach results in a more relevant analysis (Larson and Pierce, 1994). Wagenet et al. (1991) also advocated the use of simulation models for comparative studies to convert "static" soil properties into "dynamic" assessments with practical relevance. Kooistra *et al.* (1985) gave an example of the first approach in a study on the influence of different soil management types on soil structure in a loamy soil. Soil structure is characterized with morphometric techniques. A dynamic assessment focuses on the consequences of different types of soil structure on productivity and/or on environmental issues such as leaching. It may require use of simulation models as an exploratory tool. Van Lanen et al. (1992) used a simulation model to quantify differences found in soil structure by Kooistra et al. (1985) in terms of important land qualities such as moisture deficit, workability, and soil aeration. Physical measurements of hydraulic conductivity curves and moisture retention curves were used to quantify differences in soil structure as expressed by morphometric techniques.

In this study, first a comparative assessment was made between soils in two fields each at a biodynamic and a conventional farm. Secondly, data from this comparative assessment were used to predict water-limited potato yields by use of an integrated simulation model for water transport processes and crop production. Climatic data of the last 30 years were used to evaluate the effects of a range of weather conditions on water transport and crop growth in the observed soil structures.

In summary, the objectives of this study were to: (i) describe soil structure differences between identically classified soils in fields of a conventional and a biodynamic farm by morphology, by basic soil properties, and by soil hydraulic characteristics and (ii) convert these "static" soil properties into a "dynamic" potential productivity by use of a simulation model.

## MATERIALS AND METHODS

### *Soils and management*

The soils studied are located in the southwestern part of the Netherlands in young marine deposits. They are located in polders that were reclaimed in the 15th century and belong all to the same mapping unit (Mn25A, according to the Dutch soil map scale 1:50 000, Pleijter et al., 1994). Soils have a loamy texture and are classified as loamy, mixed mesic Typic Fluvaquents (Soil Survey Staff, 1975) and as Calcaric Fluvisols (FAO, 1974). These soils occupy 103,000 ha in the Netherlands, are considered to be prime agricultural land, and are mainly used as arable land.

Within this soil type, a biodynamic and a conventional farm were selected, 15 km apart, both with a management system that has been applied for about 70 years. On the biodynamic farm, the oldest one in the Netherlands, no chemical crop protection or commercial fertilizer has been applied since 1924. Animal manure and a crop rotation system with clover is intended to supply the required nutrients. However, soil tillage activities do not deviate from those at conventional farms. The selected conventional farm is a research station for arable agriculture, with emphasis on crop research. Here, nutrients are mainly applied as commercial fertilizer. Two fields were selected from each farm where measurements were made: a temporary grassland and an arable field. Abbreviations used here and crop rotations for the last 5 years for the four fields are shown in Table 1.1.

**Table 1.1. Experimental fields, abbreviations, and crop rotation for the last 5 years.**

| Field | Management | 1990 | 1991 | 1992 | 1993 | 1994 |
|---|---|---|---|---|---|---|
| Bio1 | biodynamic | bean | lucerne | lucerne | potato | barley |
| Bio2 | biodynamic | grass | grass | potato | grass | grass |
| Conv1 | conventional | sugarbeet | barley | grass | grass | grass |
| Conv2 | conventional | pea | barley | potato | sugarbeet | barley |

### *Measurements*

A thorough morphological and physical soil characterization was made. Measurements on each of the four fields were concentrated at four randomly chosen plots of 4 $m^2$. Samples were collected for standard soil characterization: texture by the pipette method (four samples per field per horizon, Gee and Bauder, 1986), bulk density by the core method (16 samples per field per horizon, Blake and Hartge, 1986), organic matter by the Walkley-Black procedure (four samples per field per horizon, Nelson and Sommers, 1982), and porosity by the density method (eight samples per field per horizon, Danielson and Sutherland, 1986). Twelve samples of 20-cm diam. and 20-cm height were used for each field to obtain saturated and near-saturated conductivity by the crust method (Booltink et al., 1991). This method allows a distinction between $K_{sat}$ when all the pores are filled with water and $K_{(sat)}$ where the soil matric pressure head is still 0 cm, but where macropores do not conduct water, which only moves through the matrix (Bouma, 1982). Undisturbed samples of 300 $cm^3$ were taken in each field and multistep outflow experiments were carried out in the laboratory yielding data for unsaturated conductivity and moisture retention (Van Dam et al., 1994). A total of 96 samples were taken for these outflow experiments, 24 from each field, eight for each horizon at 20, 50, and 80 cm below the surface. Additional retention points at pressure heads of -1000 and -16 000 cm were obtained with a pressure chamber system (Klute, 1986b). The outflow data, the conductivity data from the crust test, and the additional retention points were used to obtain parameters for analytical descriptions of the soil hydraulic characteristics. The commonly used Mualem-VanGenuchten equation (Van Genuchten, 1980) resulted in a poor fit of the measured outflow, retention points and saturated conductivity. Vereecken et al. (1989 and 1990a) noticed same problems and used for the retention curve the VanGenuchten equation with $m = 1$ and without the constriction of $n > 1$:

$$\theta(h)=\frac{\theta_s-\theta_r}{1+|\alpha h|^n}+\theta_r \tag{1.1}$$

where $\theta$ is the soil water content (cm$^3$ cm$^{-3}$), $\theta_s$ is the saturated soil water content (cm$^3$ cm$^{-3}$) and $\theta_r$ is the residual soil water content (cm$^3$ cm$^{-3}$), $h$ is matric pressure head (cm), and $\alpha$ (cm$^{-1}$) and $n$ are shape parameters. For the conductivity curve, the Gardner function (Gardner, 1958) was used:

$$K(h)=\frac{K_{sat}}{1+|\beta h|^\lambda} \tag{1.2}$$

where $K$ is hydraulic conductivity (cm d$^{-1}$), $K_{sat}$ is the saturated hydraulic conductivity (cm d$^{-1}$), and $\beta$ (cm$^{-1}$) and $\lambda$ are shape parameters.

A comparison of the highly nonlinear soil hydraulic characteristics based on the coefficients of the curves themselves is impossible but can be performed on derived properties (Wösten et al., 1986). Here, the eight individual soil hydraulic characteristics per field were compared using total and easy available water, which were defined as the amount of water between a soil water pressure head of -100 and -16 000 cm, and -100 and -1000 cm, respectively.

One mean retention and conductivity curve was calculated for each field and each horizon by averaging the eight individual curves on the basis of the pressure head, assuming normal distribution for the retention curve and geometric distribution for the conductivity curve:

$$\overline{\theta}(h)=\frac{\sum_{n=1}^{8}\theta_n(h)}{8} \qquad \log(-h)=0.0,\ 0.1,\ 0.2,\ \ldots,\ 4.0 \tag{1.3}$$

$$\overline{K}(h)=\left(\prod_{n=1}^{8}K_n(h)\right)^{\frac{1}{8}} \qquad \log(-h)=0.0,\ 0.1,\ 0.2,\ \ldots,\ 4.0 \tag{1.4}$$

where $\overline{\theta}$ is the mean retention curve and $\overline{K}$ is the mean conductivity curve.

The simulation model was validated using measured soil water contents for the four fields using time domain reflectometry (TDR, Topp et al., 1980) at four depths: 20, 45, 65, and 100 cm, near the plots where other soil properties were determined. Measurements were made biweekly during the growing season. Groundwater levels were also observed on the same dates. Weather conditions, rainfall, global radiation, temperature, and potential evaporation were measured at standard meteorological stations about 5 km from the experimental fields.

### Simulations

Soil water transport and crop growth were simulated by the WAVE package (Vanclooster et al., 1994). This package is an integrated mechanistic simulation model for water, solute, N, and heat processes in the soil and crop growth rates. For this study only the submodules for water transport and crop growth were used. The water transport module is based on the SWATRE model (Feddes et al., 1978) and has a finite difference solution scheme for solving the well-known Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[ K(\theta)\left(\frac{\partial h}{\partial z} + 1\right) - S(h)\right] \tag{1.5}$$

where $\theta$ is the volumetric water content (cm$^3$ cm$^{-3}$), $z$ is a vertical coordinate (cm), $t$ is time (d), $K$ is hydraulic conductivity (cm d$^{-1}$), $h$ is soil water pressure head (cm), and $S$ is sink term (d$^{-1}$). Root water uptake is driven by the potential transpiration and is reduced by the soil water potential and by a maximum defined uptake rate:

$$T_a = \int_{z=0}^{L_r} \alpha(h) S_{\max}(z) \partial z \quad T_a \le T_p \tag{1.6}$$

where $T_a$ is actual transpiration (cm d$^{-1}$), $z$ is depth (cm), $L_r$ is rooting depth (cm), $\alpha$ is a reduction factor as a function of the soil water potential $h$ and accounts for water deficit and water surplus, $S_{max}$ is the maximum defined uptake rate (d$^{-1}$) and $T_p$ is the potential transpiration (cm d$^{-1}$). The incorporated crop growth module SUCROS (Spitters et al., 1989) calculates crop development rate, dry matter accumulation rate of the different plant organs, and leaf area index development rate as a function of radiation, temperature, and plant phenologic parameters. The calculated potential crop growth is limited by soil water deficit or surplus according to Eq. 1.6.

Although model performance has already been tested (e.g., Diels, 1994), we chose to validate it for this particular case for the year 1994. Soils were divided into three representative horizons and soil water transport was simulated with soil layers of 2-cm thickness. The upper boundary condition, the weather, was derived from a neighbouring weather station on a daily basis. The observed groundwater levels were used as lower boundary conditions. Simulated moisture contents at three depths were compared with the moisture contents measured by TDR technique.

Land qualities are defined as: "Attributes which act in a distinct manner in their influence on the function of land for a specific kind of use" (FAO, 1976). In fact, land qualities express differences among soils in terms of criteria that are relevant to the user. Examples of important land qualities are workability, trafficability, aeration status, moisture deficit and leaching potential (Hack-ten Broeke et al., 1993). In this study the land quality "water-limited yield" was used to express and quantify differences in soil structure. The water-limited yield is defined as the yield that can be reached when only water limits yield and there are no other limitations such as nutrient shortage, occurrence of diseases, or weed growth. Both water deficit as well as surpluses were taken into account for the calculation of the water-limited yield. The water-limited yield is used to reflect differences in soil structure because only the moisture retention and the hydraulic conductivity curve differ, while other parameters in the model are identical for all sites. Leummens et al., (1995) used the same approach to compress the effect of macropores on expressions of the hydraulic conductivity curve. The WAVE simulation model was used to calculate water-limited yields, using daily weather data for a period of 30 years. Potato was used as a crop because of its susceptibility to structure differences. Rooting depth and root development were calculated by the model, but a maximum rooting depth of 40 cm was given as an input parameter. Although potato cannot, of course, be grown for 30 years on the same field, these 30 years were only used here to obtain a distribution of yields as a function of differences in soil structure and weather conditions. The lower boundary conditions were assumed to be identical for the four plots. Thus, all data were identical for the 30-years period except for soil structure.

**Table 1.2. Soil texture of the four experimental fields for depths of 20 and 50 cm.**

| | Depth 10-30 cm | | | Depth 40-60 cm | | |
|---|---|---|---|---|---|---|
| Field | clay | silt | sand | clay | silt | sand |
| | | | % | | | |
| Bio1 | 14 | 47 | 39 | 12 | 39 | 49 |
| Bio2 | 15 | 42 | 43 | 15 | 49 | 36 |
| Conv1 | 20 | 42 | 38 | 18 | 37 | 45 |
| Conv2 | 16 | 43 | 41 | 16 | 50 | 34 |

# RESULTS AND DISCUSSIONS

## *Morphology and soil properties*

Influence of the different management practices is evident mainly in the topsoil; therefore emphasis was given to the characteristics of the first 50 cm of the soil. Soil texture data are shown in Table 1.2. Basic soil properties, including a multiple-range test by the least significant difference procedure (SAS, 1985) are presented in Table 1.3. Bulk densities were lower for the biodynamic fields and organic matter contents were higher (at $P \leq 0.1$ significantly different for all fields).

**Table 1.3. Bulk density, organic matter, porosity, and saturated ($K_{sat}$) and near-saturated conductivity [$K_{(sat)}$] of the four experimental fields.**

| | Bulk density | | Organic matter | | Porosity | | $K_{sat}$ | | $K_{(sat)}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | 0-20 | 30-40 | 10-30 | 30-60 | 10-30 | 30-60 | 10-30 | 30-60 | 10-30 | 30-60 |
| | — Mg $m^{-3}$ — | | —— % —— | | — $m^3$ $m^{-3}$ — | | — cm $hr^{-1}$ — | | — cm $hr^{-1}$ — | |
| Bio1 arable | 1.52 b | 1.55 a | 2.2 a | 0.9 a | 0.39 b | 0.39 a | 2.3 a | 5.0 a | 0.3 a | 0.7 a |
| Bio2 grass | 1.47 a | 1.51 a | 3.3 b | 1.1 a | 0.42 c | 0.40 a | 10.1 a | 6.5 ab | 0.9 a | 1.1 a |
| Conv1 grass | 1.68 c | 1.59 a | 1.7 a | 1.0 a | 0.36 a | 0.40 a | 6.7 a | 10.5 b | 1.3 a | 4.3 b |
| Conv2 arable | 1.54 b | 1.52 a | 1.9 a | 1.1 a | 0.41 bc | 0.43 a | 6.6 a | 9.9 ab | 0.9 a | 2.0 a |

*Values followed by the same letter are not significantly different* ($P \leq 0.05$) *according to LSD multiple-range test.*

Morphological structure descriptions for the four fields are presented in Table 1.4. The overall impression was that structural differences were relatively small. Compaction processes, leading to large structural elements with relatively low internal porosity, had been active under both types of management, but appeared to be more pronounced for the conventional fields (Table 1.4). These relatively small structural differences were due to the similar tillage equipment being used on both farms. Structure descriptions as provided in Table 1.4 are highly qualitative and nondiagnostic.

**Table 1.4. Soil structure description of representative profiles of the four experimental fields.**

| Field | Depth (cm) | Shape | Size of peds | Grade |
|---|---|---|---|---|
| Bio1 | 0- 7 | subangular blocky | fine | moderate |
| | 7-33 | blocky with | coarse | strong |
| | | platy sand lenses | medium | strong |
| | 33-50 | apedal, massive | | |
| Bio2 | 0-25 | subangular blocky | coarse | moderate |
| | 25-45 | blocky | coarse | strong |
| | 45-50 | subangular blocky | coarse | moderate |
| Conv1 | 0- 7 | subangular blocky | very fine | strong |
| | 7-13 | blocky | fine | strong |
| | 13-50 | blocky | coarse | strong |
| Conv2 | 0-35 | blocky | coarse | strong |
| | 35-50 | apedal, massive | | |

**Table 1.5. Comparison of the eight individual soil hydraulic characteristics per field for the topsoil: total available water (between *h* = -100 and *h* = -16 000 cm), easy available water (between *h* = -100 and *h* = -1000 cm).**

| | Available water | |
|---|---|---|
| Field | total | easy |
| | $m^3\ m^{-3}$ | |
| Bio1 | 0.199 a | 0.087 b |
| Bio2 | 0.240 b | 0.092 b |
| Conv1 | 0.180 a | 0.059 a |
| Conv2 | 0.197 a | 0.080 b |

*Values followed by the same letter are not significantly different ($P \leq 0.05$) according to LSD multiple-range test.*

Mean soil hydraulic characteristics as obtained by averaging the eight individual characteristics per horizon per field are presented in Fig. 1.1. A comparison of the different soil structures by using the soil hydraulic curves was focused on comparing values of total and easy available water (Table 1.5). The biodynamic fields had a higher amount of available water, but only the highest total available water for *Bio2* and the lowest easy available water for *Conv1* were significantly different ($P \leq 0.05$).

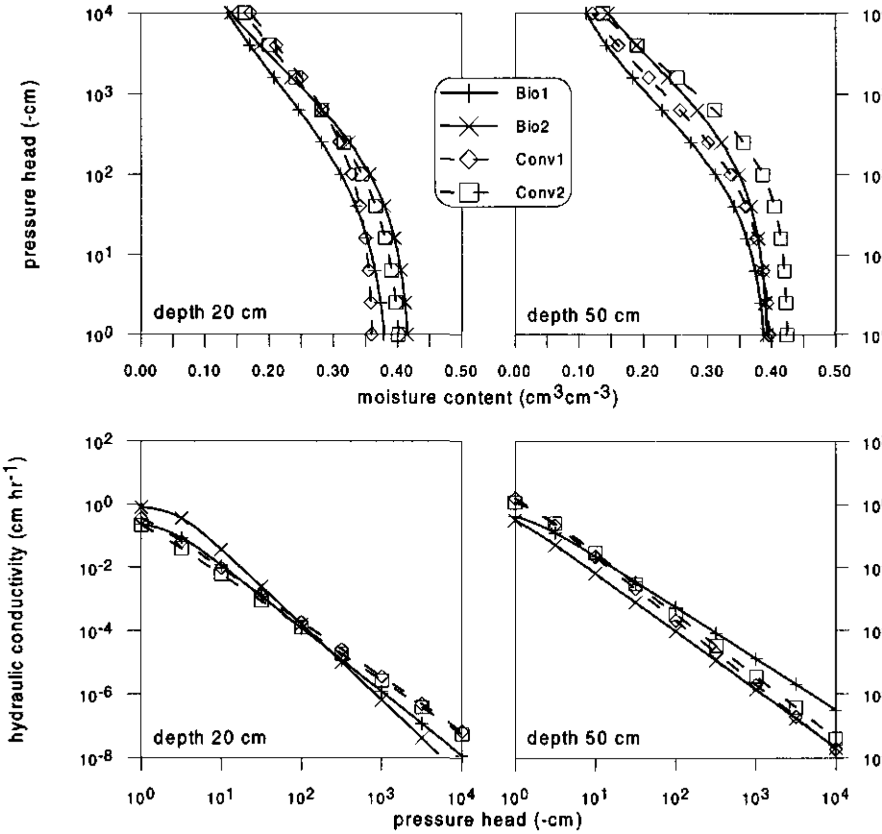

**Figure 1.1. Mean retention (upper part) and conductivity (lower part) curves for 20- and 50-cm depths as used for the simulation of the water-limited potato yield.**

### *Simulations*

Simulated moisture contents for 1994 were compared with measured moisture contents. Results are presented for two fields in Fig. 1.2. Model performance for *Conv1* and *Conv2* was quite good, with correlation coefficients of r = 0.96 and 0.97, respectively, while these values were somewhat lower for *Bio1* and *Bio2* with values of r = 0.92 and 0.82, respectively. Especially the effects of only a few summer rains could not be properly simulated for *Bio1* and *Bio2*, which was probably due to the absence of preferential flow in the model. However, overall agreement was such that the model was considered to be adequately validated to be used for this particular case study.

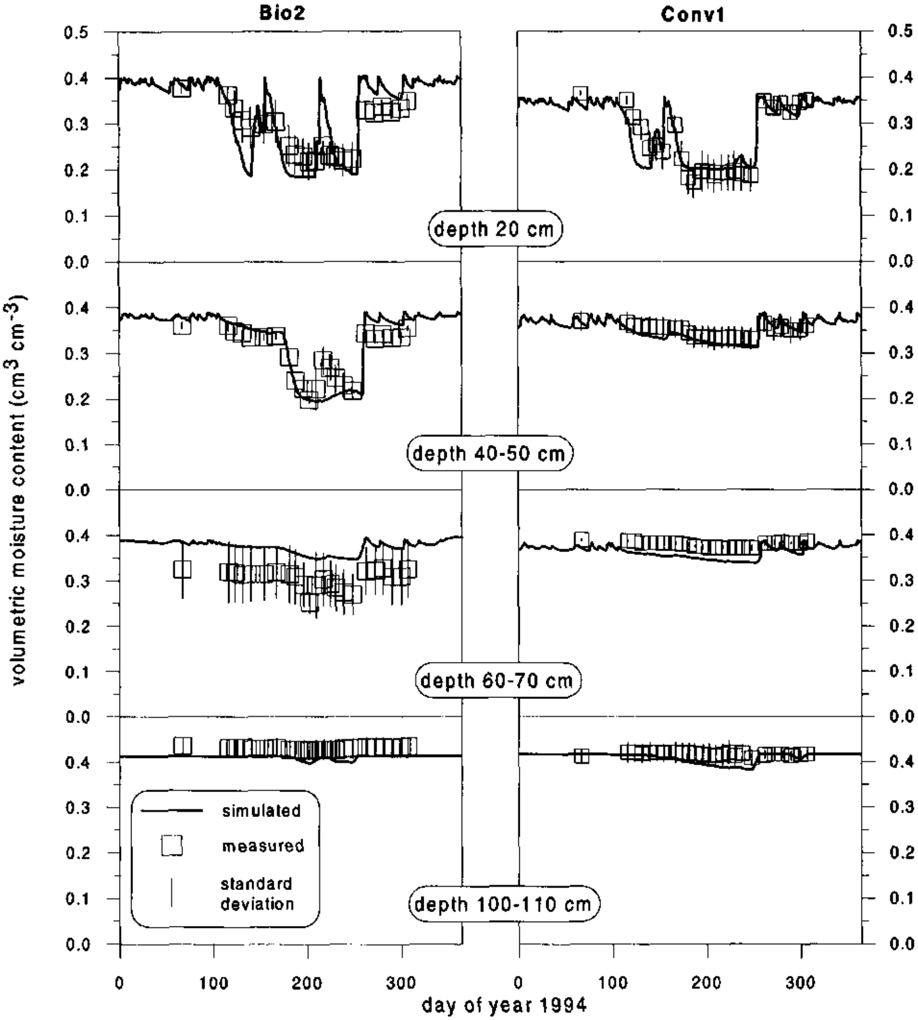

**Figure 1.2. Comparison between observed and simulated moisture contents for fields Bio2 (r = 0.82) and Conv1 (r = 0.96) for 1994, and standard deviations in observations.**

The water-limited yield for potato was calculated by the simulation model for 30 years of weather conditions. Average yields for these 30 years for the fields *Bio1*, *Bio2*, *Conv1*, and *Conv2* were, respectively: 10 200, 10 300, 9400, and 9700 kg dry matter tuber yield ha$^{-1}$, which was significantly higher for the biodynamic fields according to a LSD multiple-range test ($P \leq 0.05$). Simulated yields for these 30 years can also be used to produce a probability graph (Fig. 1.3), showing, for example, that the probability of a yield lower than 9000 kg dry matter is, respectively, 22 and 25% for *Bio1* and *Bio2* and

32 and 39% for *Conv2* and *Conv1*. Similarly, probabilities for yields to be higher than 11 000 kg dry matter are even more pronounced: 36% (*Bio1*), 42% (*Bio2*), 19% (*Conv1*), and 23% (*Conv2*). Differences between the biodynamic and conventional treatments are consistently observed for all yield levels, indicating that biodynamic management has improved soil structure when the water-limited yield under varying weather conditions is taken as an indicator. The water-limited yield is a better indicator for soil structural differences than the static bulk density and organic matter contents and the hydraulic characteristics, which have little meaning by themselves. Simulation in this study had an exploratory character indicating potentials of systems being characterized. Clearly, the potential of the biodynamic system is currently not reached: real yields are about half the value of yields in the conventional system (approximately 30 000 and 60 000 kg fresh tuber yield ha$^{-1}$, respectively).

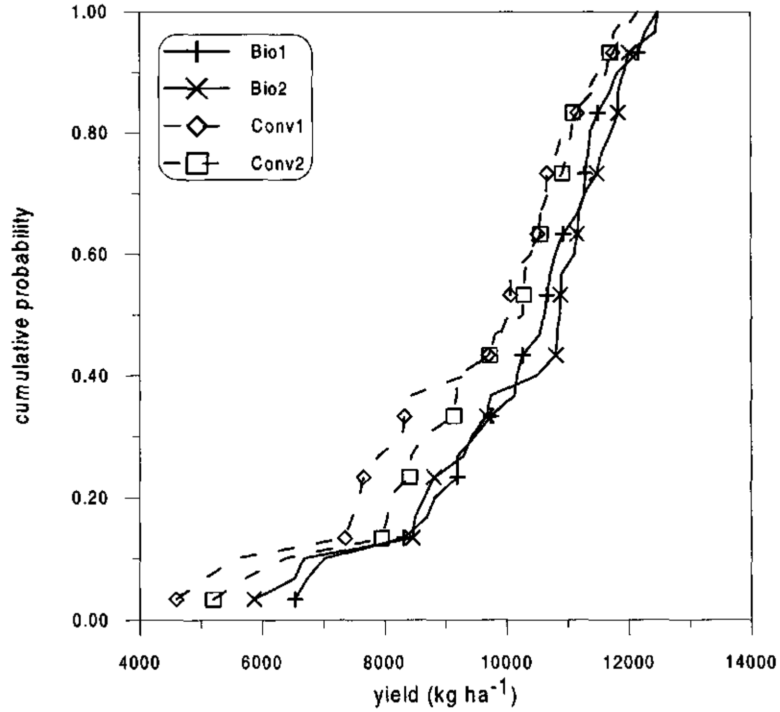

**Figure 1.3. Cumulative probability in dry matter tuber yield obtained by simulations for 30 years of weather conditions.**

## CONCLUSIONS

Differences between biodynamic and conventional management are reflected in different soil structures of surface soil. In this study four procedures were used to express these differences: (i) morphological description, (ii) static soil parameters, such as bulk density and organic matter content, (iii) static moisture retention and hydraulic conductivity data, and (iv) simulated water-limited yields under various climatic conditions. Only the last procedure provides a criterion that is quantitative, that is directly related to a practical and understandable aspect of soil behavior, and that allows an expression for the integrated effects of the highly nonlinear soil-water processes.

The biodynamic management type has a significantly higher water-limited yield than the conventional type. This indicates that biodynamic management has favorable effects on soil structure when potential productivity is taken as an indicator, thus providing a positive contribution to the sustainability analysis.

## ACKNOWLEDGMENTS

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## Chapter 2

# EFFECTS OF ECOLOGICAL SOIL MANAGEMENT ON WORKABILITY AND TRAFFICABILITY OF A LOAMY SOIL IN THE NETHERLANDS

**Abstract** Effects of ecological and conventional farming in an identical loamy soil were expressed in terms of the land qualities workability and trafficability using conditions in an old meadow as a reference. Threshold values for workability, determined by the lower plastic limit occurred at matric potentials of -120, -45 and -35 cm for the ecological, conventional and old meadow system, respectively. The corresponding trafficability threshold values, obtained by penetrometer measurements, were -160, -15 and -120 cm matric potential. An additional field-traffic experiment showed that deleterious effects of driving over a wet field were relatively small for the conventional system, and more pronounced for the old meadow and the ecological system. A dynamic simulation model for water flow was applied, using measured soil hydraulic parameters, to calculate soil water content and workable and trafficable periods during the year by use of the threshold values. Thirty years' climatic data were used in order to obtain probability graphs. The probability of a field to be workable and trafficable was largest for the conventional system, and least for the ecological system, while the old meadow had a high probability of being workable and a low probability of being trafficable. The occurrence of five consecutive days with an appropriate topsoil moisture content for workability and trafficability was considered to represent the potential start and end of any growing season. The probability of being able to sow or plant at what is considered the optimum date by agronomists was high for the conventional field (77% for cereals; 93% for potatoes and sugar beet) and low for the old meadow (10% and 33% respectively) and very low for the ecological field (0% and 17% respectively). The moisture supply capacity of the soil, defined as the ratio between actual and potential transpiration, was most favourable for the old meadow, least favourable for the conventional field and with the ecological field in between. Potential productivity of the ecological system was thus higher than the conventional system, but the risk of compaction was higher as well, putting relatively high demands on the management abilities of ecological farmers.

## INTRODUCTION

Traditional land evaluation uses land qualities to define soil suitabilities for different land utilization types (e.g. FAO, 1976). A land quality is defined as "a complex attribute of land which affects its suitability for specific uses in a distinct way" (FAO, 1976). Modern mechanized agriculture requires soil to be able to carry mechanical loads during tillage, seeding and planting management practices. Meadows should, in addition, have the capacity to carry cattle. The land quality trafficability has been used to characterize the bearing capacity of soil and can be defined as: "the period during the year when soil traffic is possible without causing unfavourable compaction". For arable land, another mechanical land quality which is important relates to workability, defined as: "the period during the year when tillage is possible with positive effects on soil structure". Of course, these "positive effects" have to be specified as well, but they are quite different in different soils. The term "positive" thus allows soil-specific details to be defined.

The land qualities trafficability and workability can be split up in two components. The first component is the threshold value for trafficability or workability, expressed in moisture content or matric potential, stating whether trafficking or working is possible. The second component is the period during which the soil is trafficable or workable, which is a function of the soil moisture regime and the threshold values.

Simulation techniques can be used successfully to estimate soil moisture regimes as a function of changing weather conditions and water-table fluctuations as was demonstrated by Van Lanen et al. (1987, 1992). In addition to the soil-water content at any time, threshold values have to be defined for the water content, above which unfavourable compaction or puddling is likely to occur (e.g. Bouma and Van Lanen, 1987).

Conventional land evaluation focuses on a given soil type and defines its suitability for a wide range of land utilization types. However, different forms of management may have major and lasting effects on soil properties to the extent that soil behaviour may significantly change (e.g. Bouma, 1994).

This study was made in a Typic Fluvaquent, one of the most productive agricultural soil types of the Netherlands and compared the effects of different types of management on trafficability and workability in three fields. One field was part of the oldest ecological farm in the Netherlands (Loverendale = *Bio*), one field belonged to an experimental farm with more conventional management (Rusthoeve = *Conv*) and the third field was an old meadow (De Visser = *Perm*). The latter soil is considered to represent reference conditions for this particular soil type in terms of soil structure and organic matter content.

Of particular interest are differences between the *Bio* and *Conv* fields, in comparison with field *Perm*, because ecological farming has the implicit objective of increasing the sustainability of farming systems. A prime objective of this study was therefore to evaluate how observed differences among the three fields could be interpreted in terms of sustainability criteria.

The FAO (1993) definition for sustainable land management was followed here: "Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: (i) maintain or enhance production and services, (ii) reduce the level of production risk, (iii) protect the potential of natural resources and prevent degradation of soil and water quality, and (iv) be economically viable and socially acceptable".

This study focused on: (i) defining differences between the three fields, as expressed by the two land qualities, and (ii) expressions of these differences in terms of sustainability indicators as implicitly defined by FAO (1993): production, production risk, quality of soil and water and economic and social viability.

# MATERIALS AND METHODS

### *Soils and management types*

The study area was located in the South-Western part of the Netherlands in the province of Zeeland. The soil type of interest, a mixed mesic Typic Fluvaquent (Mn25a according to the soil map of the Netherlands 1:50 000) is widespread over the Netherlands and is very suitable for agricultural production. Within this soil type three fields were selected where measurements were concentrated. These fields are considered to be similar in the first place and differences in soils are only a result of the different types of management. Evidence for this could be found in the origin of the soils. The three fields are located in polders, which were reclaimed in the 15th century, within similar geological setting (Pleijter and Beekman, 1985). The texture data of the three fields, which is not influenced by management, are similar (Table 2.1).

**Table 2.1. Soil particle-size data for the three fields. Clay is < 2 µm, silt is 2 - 50 µm, and sand is 50 - 2000 µm. *Bio* is ecological temporary grassland, *Conv* is conventional temporary grassland, and *Perm* is permanent grassland.**

| Field | Depth 10-30 cm | | | Depth 40-60 cm | | |
|---|---|---|---|---|---|---|
| | clay | silt | sand | clay | silt | sand |
| | | | % | | | |
| Bio | 15 | 42 | 43 | 15 | 49 | 36 |
| Conv | 20 | 42 | 38 | 18 | 37 | 45 |
| Perm | 15 | 43 | 42 | 16 | 53 | 32 |

The first field (*Bio*) has been managed according to ecological principles, which means that no chemical fertilizer or chemical crop protection has been applied for more than 80 years. Emphasis was given to maintaining favourable soil structure by using organic fertilizer and by a soil-structure improving crop rotation. However, soil tillage activities can be categorised as conventional and consist of ploughing in Autumn to a depth of 25 cm as the main tillage activity. The second field (*Conv*) was situated on an experimental farm where management can be characterised as conventional with similar tillage activities as *Bio*. Both fields were currently used as temporary grassland, the *Bio* field for two years and the *Conv* field for three years. Crop rotations for *Bio* and *Conv* were comparable: three years grass followed by three or four years arable use. Finally, a field with permanent grassland was selected (*Perm*), representing a soil structure with a more or less natural character. Management for all the three fields has been constant for the last few decades, which is an essential condition because effects of management can take decades to come to a state of equilibrium (Phillips and Phillips, 1984).

Basic soil data (Table 2.2) demonstrate the effect of different management on the topsoil and the comparable properties for the soil layer in the depth range 30 to 60 cm. From field *Conv* to *Bio* to *Perm* trends in surface soil were clear: an increase of organic matter, porosity and saturated hydraulic conductivity.

**Table 2.2. Basic soil properties for the three fields, *Bio* is ecological temporary grassland, *Conv* is conventional temporary grassland and *Perm* is permanent grassland. $K_{sat}$ is saturated conductivity including macropores and $K_{(sat)}$ is saturated conductivity without macropores (Booltink et al., 1991).**

| | Bulk density | | Organic matter | | Porosity | | $K_{sat}$ | | $K_{(sat)}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Depth (cm) | 0-20 | 30-40 | 10-30 | 30-60 | 10-30 | 30-60 | 10-30 | 30-60 | 10-30 | 30-60 |
| | — $Mg\ m^{-3}$ — | | —— % —— | | — $m^3\ m^{-3}$ — | | — $cm\ hr^{-1}$ — | | — $cm\ hr^{-1}$ — | |
| Bio | 1.47 b | 1.51 a | 3.3 b | 1.1 ab | 0.42 b | 0.40 a | 10.1 a | 6.5 a | 0.9 a | 1.1 a |
| Conv | 1.68 c | 1.59 a | 1.7 a | 1.0 a | 0.36 a | 0.40 a | 6.7 a | 10.5 a | 1.3 a | 4.3 b |
| Perm | 1.38 a | 1.49 a | 5.0 c | 1.4 b | 0.46 c | 0.40 a | 43.9 a | 8.3 a | 3.9 a | 2.0 a |

*Values followed by the same letter are not significantly different ($P=0.05$) according to LSD multiple-range test.*

Morphology of the topsoil reflected also the effects of the different management types. The *Bio* field had large peds with relatively low internal porosity. The structure grade of the peds was moderate for the root zone, but strong below the root zone. The same, but in a somewhat more pronounced fashion, holds for the *Conv* field. Here the grade of the peds was strong for the whole topsoil, but the size of the peds in the root zone was reduced from coarse to fine. The similarity between the morphology of the *Bio* and *Conv* fields could be explained by more-or-less comparable tillage practices, although the higher organic matter and the crop rotation of the *Bio* field led to a somewhat less compacted structure. The *Perm* field had a loose structure with a high organic matter content with many biologically induced pores. Below the root zone the structure was somewhat more compact.

### Threshold values for workability and trafficability

The threshold value for workability is defined as "the soil moisture status, expressed in moisture content or matric potential, at which tillage is possible with positive effects on soil structure". If the soil is drier than the threshold value tillage activities can be performed without structure deterioration. However, a soil can also be too dry for optimal tillage. The power required for tillage will increase and moreover the operation itself is less effective as the cohesive forces in the soil are too strong for optimal crumbling. Because the latter occurs rarely in the study area, this aspect is excluded.

The well-known Atterberg test was performed to obtain the lower plastic limit for the three fields (Atterberg, 1911). Samples were taken at four randomly chosen plots at each field from the top 20 cm, and the lower plastic limit was determined on 10 replicates for each sample. A drawback of this method could be the subjectivity in the judgement of the state of the plasticity of the sample (Terzaghi et al., 1988). To avoid this subjectivity and to evaluate the corresponding error a total of 120 determinations were handled in random order and some determinations were also independently done by two operators. The lower plastic limit obtained, expressed as a gravimetric moisture content, was converted to volumetric moisture content by multiplying it by the bulk densities of the samples.

The threshold value for trafficability, also expressed in moisture content or matric potential, is the soil moisture status at which "soil traffic is possible without causing unfavourable compaction". Penetrometer measurements are useful for determining the trafficability of a field. For the three fields with the different management types, the relation between soil moisture content and penetration resistance was obtained. By combining this relation with a critical penetration resistance for trafficability, the threshold value for trafficability was estimated for the three fields. Critical penetration resistances for trafficability can be found in literature (e.g. Rounsevell, 1993). However, values are obtained with a large diversity of penetrometers and measurement techniques. Fritton (1990) developed a procedure that can be used to compare penetrometer measurements by transforming measurements to a standard penetrometer with cone diameter 2 mm, cone angle 30° and penetration speed 0.5 mm $min^{-1}$. From comprehensive field measurements it appears that penetration resistances lower than 0.5 MPa are insufficient and values higher than 0.7 MPa are sufficient (Van Wijk, 1988). These critical resistances were obtained with a penetrograph with cone diameter 25 mm (base 5 $cm^2$), cone angle of 30° and an unknown but low speed. Transforming these resistances to a standard according to Fritton (1990), resulted in the same values because corrections for cone size and angle were of the same magnitude but opposite in sign.

Penetration resistances in this study were obtained by a penetrograph with cone base area of 1 $cm^2$ and tip angle of 60°. All penetration data were transformed to a standard as described before. The depth range 15 to 40 cm is considered to be the most important in determining soil trafficability (Kogure et al., 1985). In this work, the penetration resistance at 20 cm was used as the critical depth for trafficability. On each of the three fields, four plots were randomly selected and in each plot penetration resistance was measured at 10 locations. At the same time volumetric moisture contents were measured by the Time-Domain Reflectometry technique (Topp et al., 1980) also at 20 cm depth.

Additionally, an experiment was made to evaluate the effects of traffic during wet periods on the topsoil. On each field three plots were slowly wetted and equilibrated overnight. A tractor with a mass of 3100 kg drove twice over the plots at a speed of 2 km $hr^{-1}$. Inside the tracks, and just outside the tracks, infiltration measurements were carried out with small infiltrometers (Falayi and Bouma, 1975). A critical infiltration rate of 5 cm $d^{-1}$ was assumed to represent a threshold value; indicating serious compaction because ponding of water is likely considering winter rainfall rates (Bouma, 1981). Also samples of 100 $cm^3$ from the topsoil in, and just outside, the tracks were taken to measure bulk densities by the core method (Blake and Hartge, 1986), porosities by the density method (Danielson and Sutherland, 1986) and the air-filled porosity at a weight matric potential of -100 cm by the water desorption method (Danielson and Sutherland, 1986).

### Simulation of water regimes

In order to obtain periods for workability and trafficability the threshold values should be compared with the soil moisture status during the year. Water contents and matric potentials were simulated with a revised version of the model WAVE (Vanclooster et al., 1994). This model is an integrated mechanistic simulation model for water, solute, nitrogen, heat and crop-growth processes. Model performance in general was tested by Diels (1994) and by Vanclooster (1995), while performance for this specific case was tested by Droogers and Bouma (1996). For this study only the submodule for water transport was applied. Actual transpiration was simulated by reducing the potential transpiration to a function of the matric potential of the soil according to the root-water uptake function (Feddes et al., 1978). Upper and lower boundary conditions, variables in the root-water uptake function and rooting depth were all assumed equal for the three fields in order to obtain results which were only a function of soil structure as expressed by the associated soil-physical characteristics. Although actual rooting depth and potential rootability of the fields were not identical, a value of 25 cm was used for the three fields. This was done because rooting depth has a significant influence on simulated water regimes, while this study was focused on the effects of soil structure on workability and trafficability. Soil hydraulic functions for each recognized soil layer, retention and conductivity curves, were determined on eight replicates for each field by combining multi-step outflow data (Van Dam et al., 1994), crust data (Booltink et al., 1991) and some additional retention points (Fig. 2.1). Simulations were performed with climatic data from the last 30 years in the Netherlands in order to express workability and trafficability in terms of a probability distribution.

**Table 2.3. Threshold values for workability and trafficability for ecological (*Bio*), conventional (*Conv*) and permanent (*Perm*) grassland. Workability threshold values were obtained by the Atterberg test. Trafficability was determined by the relation between penetration resistance (PR) and moisture content $\theta$, and the threshold value was defined by a PR of 0.7 MPa.**

| | Workability | | | | Trafficability | | | |
|---|---|---|---|---|---|---|---|---|
| | threshold value | | | | regression equation | | threshold value | |
| Field | $\theta$ mean | $\theta$ sd | *n* | *h* | PR($\theta$) = | $R^2$ | $\theta$ | *h* |
| | — $cm^3$ $cm^{-3}$ — | | | cm | | | $cm^3$ $cm^{-3}$ | cm |
| Bio | 0.35 | 0.016 | 40 | -120 | $5.5 - 14.3 \cdot \theta$ | 0.67 | 0.34 | -160 |
| Conv | 0.34 | 0.017 | 38 | -45 | $5.3 - 13.0 \cdot \theta$ | 0.96 | 0.35 | -15 |
| Perm | 0.41 | 0.043 | 29 | -35 | $5.9 - 14.2 \cdot \theta$ | 0.98 | 0.37 | -120 |

# RESULTS

## *Threshold values*

Results of the threshold values for workability are presented in Table 2.3. Standard deviations for the three fields were remarkably small. Only the standard deviation for *Perm* was slightly larger, due to some small differences in the plots selected. Independent determination of the lower plastic limit by two operators on 10 samples gave a significant difference by the two-paired t-test for a probability level of $< 0.05$, indicating that the test yielded independent results. Threshold values in volumetric moisture content were highest for *Perm* and were in the same order of magnitude for *Conv* and *Bio*. Threshold values were also expressed in terms of matric potential using retention curves. These values were in the same order of magnitude for both the *Conv* and the *Perm* fields and indicate that soils could be workable under a broad range of moisture conditions. The *Bio* field was only workable when the soil had a matric potential of less than -120 cm.

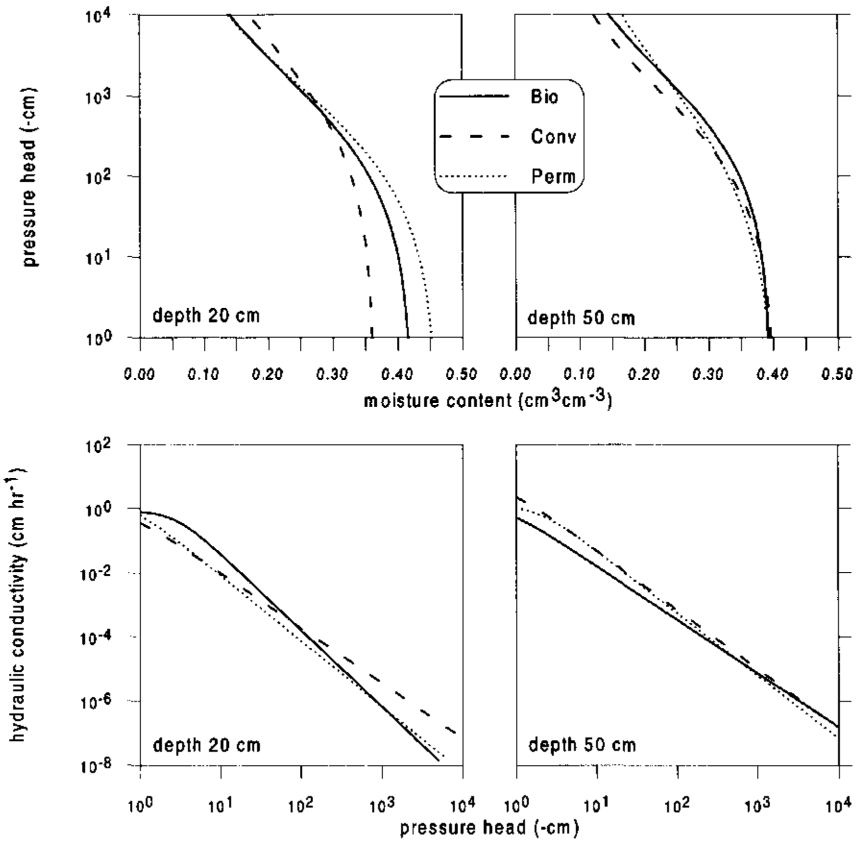

**Figure 2.1. Water retention and hydraulic conductivity curves for the ecological (*Bio*), conventional (*Conv*) and permanent (*Perm*) grassland obtained by crust-method and multi-step outflow. Each curve was obtained by averaging 8 individual curves.**

Threshold values for trafficability were obtained by a linear fit between penetration resistance and moisture content and were associated with a critical threshold value of 0.7 MPa (Fig. 2.2 and Table 2.3). Variation in measured penetration resistances was quite high, especially for the *Bio* field. The rather compacted *Conv* field (Table 2.2) appeared to be trafficable under almost all moisture conditions. It appears that only during very wet circumstances (matric potential > -15 cm) traffic has a negative influence on the soil. The other two fields should be much drier before trafficking can occur without adverse effects.

Frequently workability and trafficability are not distinguished and only one value for machinery accessibility is used (e.g. Rounsevell, 1993). Considering matric potential threshold values instead of moisture content threshold values, provides a comparison independent of the porosity of the soil. From this study it appeared that for the *Bio* and the *Perm* field the workability threshold value was higher than the one for trafficability, and for *Conv* the opposite was true. For *Bio* and *Perm* probably the relatively high organic matter content was the determining factor for the workability threshold value and the relatively low bulk density is likely to have been the most important factor for the trafficability threshold value. For *Conv* the high bulk density has probably resulted in the relatively high trafficability of this soil.

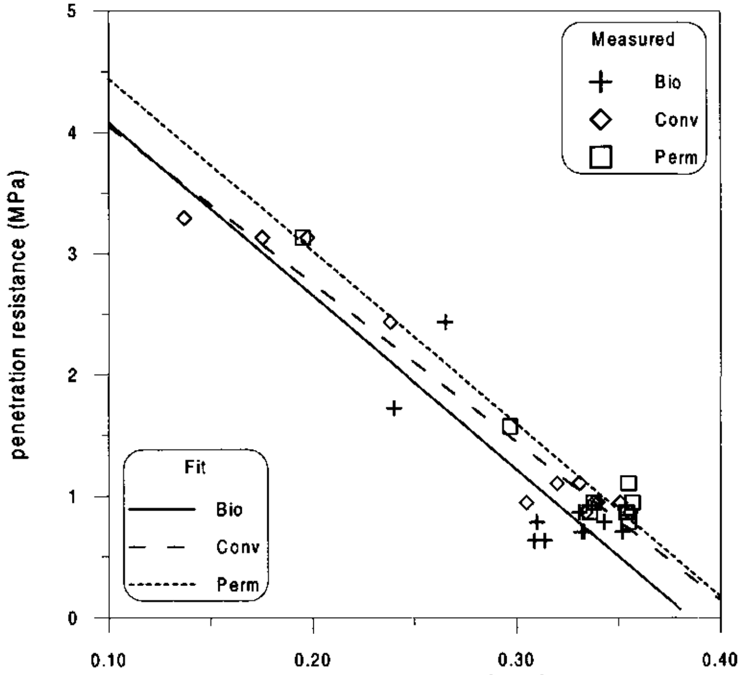

**Figure 2.2. Relation between penetration resistance and volumetric moisture content obtained by penetrograph measurements and Time-Domain Reflectometry respectively. Regression data are presented in Table 2.3.**

The results of the traffic experiment on the wet plots are presented in Table 2.4. Reduction in infiltration rate as a result of driving over the wet fields was substantial for the *Bio* and *Perm* fields. The infiltration rate of the *Conv* field was much less reduced by the traffic even in the saturated plot. Differences for the *Conv* field were not significant at 5% level, due to the large variation in infiltration rates. Traffic for this field, even under very wet circumstances, did not decrease the infiltration capacity substantially and values were not lower than 4 cm $d^{-1}$ which is close to the critical rate for Dutch climatic conditions of 5 cm $d^{-1}$. The infiltration rate of *Perm*, which was initially high, decreased substantially below the critical level for very wet conditions. Reduction in infiltration capacity in the *Bio* field was strong and decreased to almost zero in the wettest plot. Defining quantitative threshold values for trafficability with this experiment was not possible, as a consequence of the relatively small number of measurements and the quite high variation in results. In general it can be concluded, taking the critical infiltration rate of 5 cm $d^{-1}$ as the threshold value, that *Conv* is trafficable during almost all moisture conditions, *Bio* needs a matric potential less than -60 cm to be trafficable, and *Perm* needs a value between $h$ = -60 and -20 cm. These results are more or less in agreement with the threshold values obtained by the penetrometer method, except for *Perm*. Probably differences in soil conditions for the top 10 cm, used in the traffic experiment, and for 20 cm depth, used for the penetration measurements, deviate more for *Perm* than for *Bio* and *Conv*.

**Table 2.4. Effects of traffic on wet plots for the three fields compared with the untrafficked plot for the upper soil layer (0-10 cm). Initial moisture status is the matric potential when the tractor drove over the plots. Aeration status is defined as the porosity between saturation and matric potential of -100 cm.**

| | Untrafficked | Wet | Wetter | Wettest |
|---|---|---|---|---|
| | | **initial matric potential (cm)** | | |
| Bio | | -60 | -15 | 0 |
| Conv | | -150 | -15 | 0 |
| Perm | | -60 | -20 | 0 |
| | | **infiltration rate (cm $d^{-1}$)** | | |
| Bio | 34 a | 2.1 b | 0.4 b | 0.0 c |
| Conv | 16 a | 4.3 a | 4.9 a | 5.0 a |
| Perm | 179 a | 14.2 b | 1.6 c | 1.0 c |
| | | **bulk density (Mg $m^{-3}$)** | | |
| Bio | 1.42 a | 1.43 ab | 1.44 ab | 1.52 b |
| Conv | 1.44 a | 1.52 a | 1.46 a | 1.45 a |
| Perm | 0.96 a | 1.01 a | 0.97 a | 0.96 a |
| | | **porosity ($m^3$ $m^{-3}$)** | | |
| Bio | 0.44 a | 0.44 ab | 0.41 ab | 0.41 b |
| Conv | 0.43 a | 0.41 a | 0.42 a | 0.44 a |
| Perm | 0.60 a | 0.59 a | 0.60 a | 0.60 a |
| | | **aeration status ($m^3$ $m^{-3}$)** | | |
| Bio | 0.05 a | 0.04 ab | 0.03 b | 0.02 c |
| Conv | 0.06 a | 0.05 ab | 0.03 b | 0.04 ab |
| Perm | 0.10 a | 0.07 a | 0.08 a | 0.07 a |

*Values followed by the same letter, in horizontal direction, are not significantly different (P=0.05) according to LSD multiple-range test.*

Bulk densities showed almost no trafficking effects as these were overwhelmed by the small-scale field variability. Bulk densities for the uncompacted *Perm* field were very low as a result of the high amount of organic matter and the large amount of roots in the topsoil. However the air content at a matric potential of -100 cm decreased for all fields following traffic, but no clear correlation between the degree of wetness and the decrease in air content could be observed.

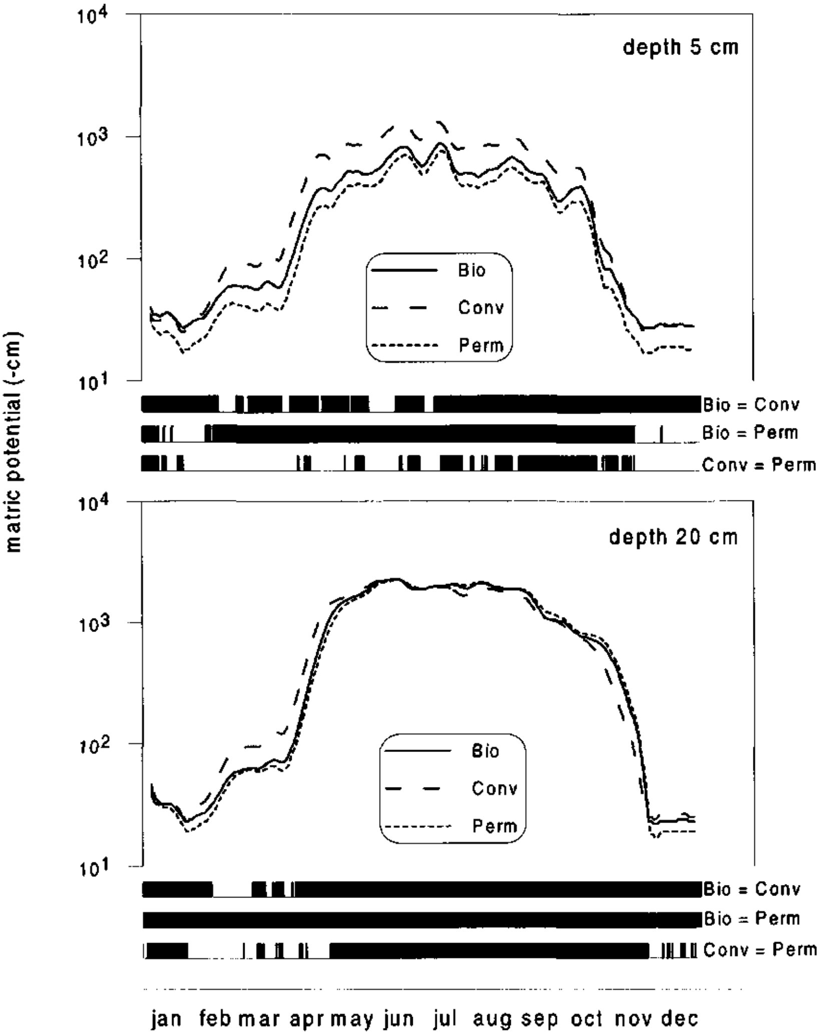

**Figure 2.3. Simulated matric potential profiles obtained by averaging the results of simulation with weather data from the last 30 years in the Netherlands. Results are plotted as running average with a window width of 9 days. Periods during the year with no significant differences (LSD multiple-range test with P = 0.10) between the fields are indicated by black bars.**

### Water regimes

With the simulation model WAVE, moisture contents, matric potentials and change in evaporation were calculated using 30 years of climatic data. The average weight matric potentials for these 30 years are presented in Fig. 2.3 for depth 5 cm and 20 cm. The top 5 cm of field *Conv* was driest during most parts of the year. The *Perm* field tended to be wetter than the other fields. Differences for depth 20 cm were small, especially during the summer period. According to the multiple-range test, *Bio* and *Perm* hardly ever differed; *Conv* and *Perm* differed significantly during spring and during December (Fig. 2.3). Water deficits, defined as the difference between potential and actual transpiration, were on average 79, 91 and 72 mm per year for *Bio*, *Conv* and *Perm*, respectively. A negative correlation was found between moisture deficit and soil moisture status: the *Conv* field had the highest moisture deficit and also the driest topsoil while the opposite occurred for field *Perm*.

Simulations with 30 years of climatic data allowed definition of moisture supply capacity not only in terms of averages but also in terms of probability of occurrence. The ability of the soils to supply the evaporative demand of a plant, expressed as the actual transpiration divided by the potential transpiration over a whole year, is given in Fig. 2.4. Clearly, *Perm* had the highest probability of satisfying the evaporative demand, the contrary applied for the *Conv* soil.

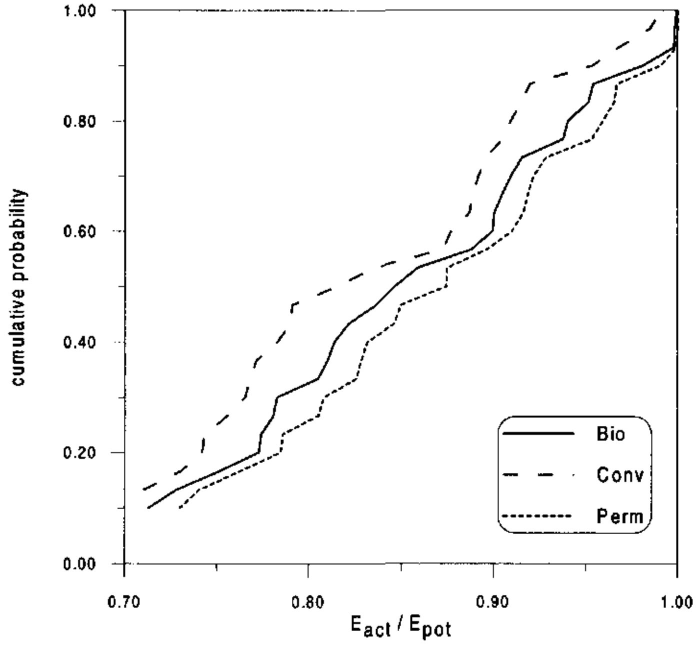

**Figure 2.4. Moisture supply capacity of the soils, expressed as the ratio between actual transpiration ($E_{act}$) and potential transpiration ($E_{pot}$), expressed as cumulative distribution obtained from simulations with 30 years of climatic data.**

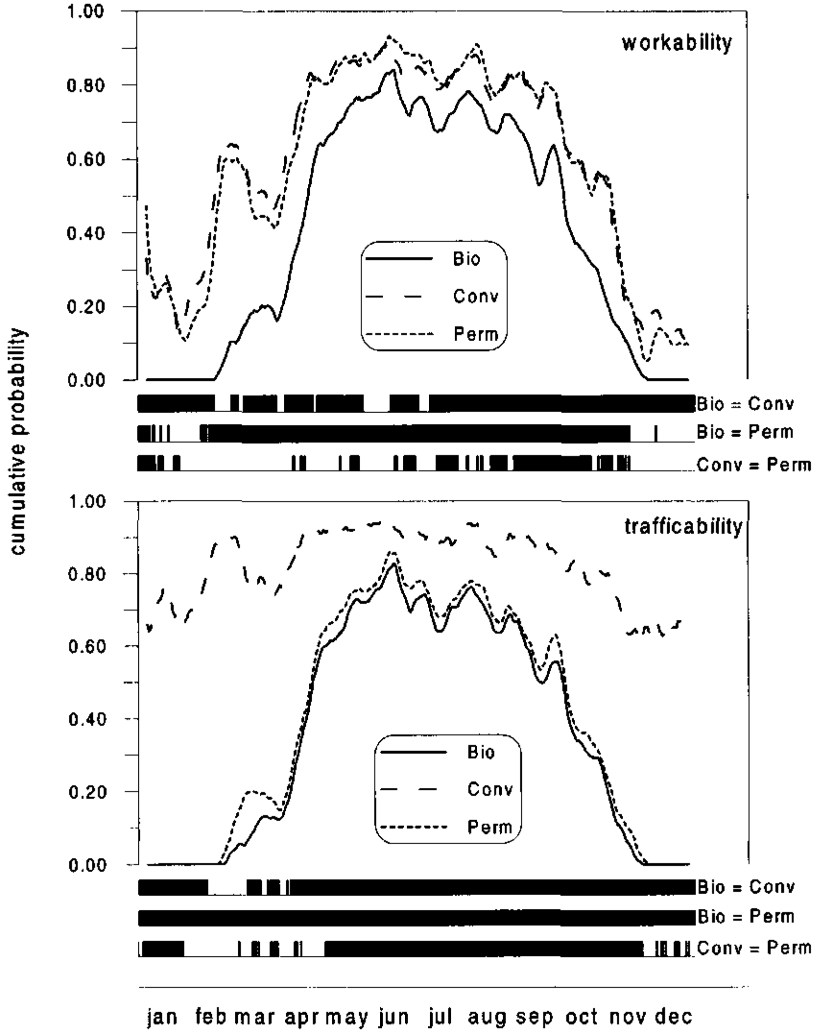

**Figure 2.5. Probability distribution of trafficability and workability during the year. Figures were obtained by combining simulated matric potentials from 30 years of climatic data with threshold values for workability and trafficability as given in Table 2.3. Periods during the year with no significant differences (LSD multiple-range test with P = 0.10) between the fields are indicated by black bars.**

### *Workable and trafficable periods*

Simulated matric potentials for the surface soil were transformed to workable and trafficable days by reference to the threshold values. The 30-year simulations of soil moisture regimes resulted in probability functions for the trafficability and workability (Fig. 2.5). Workability of the *Conv* and *Perm* field were almost equal. Workability of *Bio* was significantly lower especially during spring and autumn. The trafficability of field *Conv* was highest. This result was in agreement with the results of the field-traffic experiment on wetted plots.

Length of growing season and the first-dry period in Spring are important factors for crop growth. Using matric potential data and threshold values for workability and trafficability the start and the potential length of the growing season can be estimated. The start of growing season was defined as the first period of five days in a year when the field was both trafficable and workable. End of the growing season was defined as the last period of five days when conditions were favourable for workability and trafficability (Fig. 2.6). Optimum sowing or planting dates for the three most important crops in the Netherlands are 1 March for cereals and 20 March for potatoes and sugar beet (Van Wijk, 1988). Applying these dates for the three fields resulted in the conclusion that the optimal condition for sowing cereals can be reached in 0%, 77% and 10% of the years for respectively *Bio*, *Conv* and *Perm*. Figures for sugar beet and potatoes were 17%, 93% and 33% respectively.

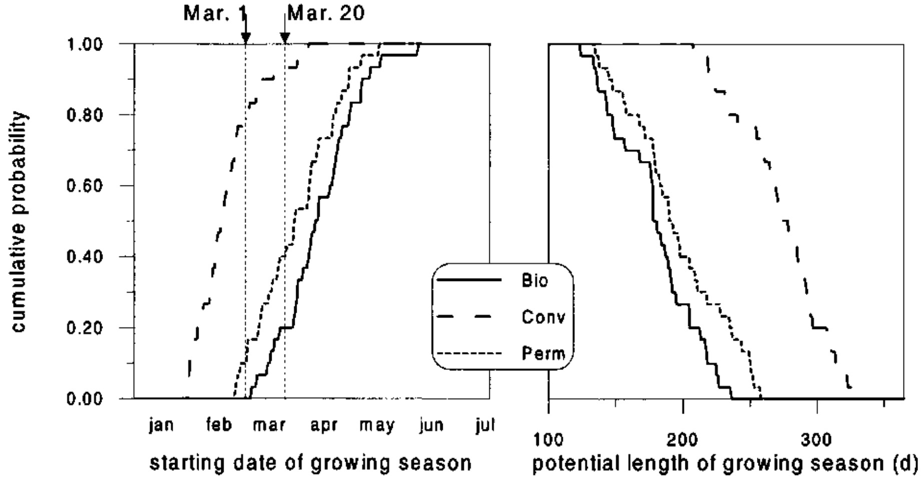

**Figure 2.6. Cumulative probability of the start and the length of the growing season for *Bio*, *Conv* and *Perm*. Start of growing season is defined as the first period in the year with 5 continuous workable and trafficable days. Length of growing season is the period from the start of the growing season till the last 5 continuous workable and trafficable days. Optimum sowing or planting dates of cereals (1 March) and potatoes and sugar-beet (20 March) are also indicated.**

# DISCUSSION

Three different types of soil management have significantly changed the properties of a particular soil type in the Netherlands, which is considered to be a prime agricultural soil. Ecological farming has increased the organic matter content of the surface soil significantly, as compared with conventional, high input farming even though the content is still less than that of permanent grassland. The bulk density of surface soil was highest under conventional farming and the water holding capacity, as expressed by moisture retention curves, was the lowest. This explains the observed high trafficability under conventional farming, because both the high density and the relatively low water contents during the year contribute to this high trafficability (Fig. 2.5). Workability was also highest for conventional farming because of significantly different threshold values, corresponding with a moisture content associated with soil plasticity. Under conventional farming the soil is workable when the matric potential is lower than -45 cm, while ecological farming is associated with a value of at most -120 cm. At the same time, water contents in surface soil were higher for the ecological field. The combined effects of different threshold values and moisture regimes, result in a significantly lower workability for ecological farming, as shown in Fig. 2.5.

The implications of differences in trafficability and workability are major, as is illustrated in Fig. 2.6. Under the assumptions made, the start of the growing season and its potential length are, respectively, significantly later and shorter under ecological farming.

However, the higher water holding capacity of surface soil under ecological farming has a favourable effect on water supply to crops and water deficits (calculated for a 30-year period) were therefore significantly lower under ecological management. Droogers and Bouma (1996) showed that potential production levels under ecological farming were significantly higher than those under conventional management.

This exploratory study indicates, therefore, that, in this particular type of soil, ecological farming results in a more productive soil but only when the farmer is particularly careful about driving on the land and about selecting the appropriate moment and equipment for tillage. Clearly, higher management qualities are required than with conventional farming where trafficability and workability are much less critical: it will be much easier to avoid mistakes. These exploratory results are also an incentive to explore alternative soil-traffic and tillage procedures for ecological management practices, because conventional procedures were used for both management systems. Possibilities could include use of special tyres or traffic lanes and minimum tillage systems. A discussion of alternative forms of ecological management is beyond the scope of this paper, but can be found elsewhere (e.g., Lytton-Hitchins et al., 1994). However, this study illustrates how exploratory use of simulation modelling can initiate development of innovative forms of management, by defining critical aspects of current management procedures.

Considering criteria for sustainable management, discussed at the beginning of this paper, the conclusion can be that ecological farming in this type of soil has increased the level of sustainability by its higher potential production level and its lower production risk because of a higher moisture supply capacity. The aspect of degradation of soil quality has been specified in this paper by showing that compaction (a form of degradation) is more likely to occur under ecological farming, at least when conventional tillage practices are used. However, when the farmer is very careful in selecting his moments of soil travel and tillage, the problem can probably be overcome. Avoiding compaction probably requires development of alternative procedures for soil traffic and tillage which would reduce the probability that compaction would occur. Effects of such alternative techniques could again be evaluated with procedures presented in this paper, to assess their effects on sustainability aspects.

## ACKNOWLEDGMENTS

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# PART II

# Physical processes in space and time

Chapter 3

Droogers, P. 1997. **Effects of spatial and temporal variability on simulated transpiration ratios.** J. of Hydrol. (in press).

Chapter 4

Droogers, P. 1997. **Time aggregation of nitrogen leaching in relation to critical threshold values.** J. of Contaminant Hydrol. (in press).

Chapter 5

Droogers, P., A. Stein, J. Bouma, and G. de Boer. 1997. **Describing macro-porosity derived from staining patterns under field conditions.** Geoderma (submitted).

Chapter 6

Droogers, P., F.B.W. van der Meer, and J. Bouma. 1997. **Water accessibility to plant roots in different soil structures occurring in the same soil type.** Plant and Soil 188: 83-91.

# Chapter 3

# EFFECTS OF SPATIAL AND TEMPORAL VARIABILITY ON SIMULATED TRANSPIRATION RATIOS

**Abstract** Sustainability studies are increasingly needed to determine management systems that protect the environment and maintain production potentials. Whether these analyses are performed by field experiments or by computer modelling, defining the appropriate spatial and temporal scales is essential. For three management types within one soil series in The Netherlands, the land quality indicator "transpiration ratio", $E_{\mathrm{ratio}}$ (ratio between actual and potential transpiration), was determined using a simulation model of water flow in the unsaturated zone. Soils were characterised by eight profiles per management type in which measurements of the retention and hydraulic conductivity characteristics were made. Variation in weather data was described by 30 years of historical data. Soil hydraulic characteristics were used as individual data and as averaged data. Differences in $E_{\mathrm{ratio}}$ obtained by using individual soil data rather than averaged data were not significant, but $E_{\mathrm{ratio}}$ values for the three management types were significantly different (0.79, 0.81 and 0.83). The results of the 30 years were used to analyse the effect of the time over which an experiment is evaluated, on the $E_{\mathrm{ratio}}$. The differential of variance indicated that the length of an experiment should be at least seven years in order to reduce the effect of the variable weather conditions.

## INTRODUCTION

Methodology for defining sustainable land management is increasingly needed to overcome environmental problems and to maintain production potentials (FAO, 1993). Analysis of the effects of different management practices on soil properties can be used to evaluate the sustainability of the distinguished management systems. Sustainability can be evaluated by "land quality indicators", defined as "measures, or values derived from variables, that provide estimates of the condition of land relative to human needs, changes in this condition, and human actions which are linked to this condition" (Pierie et al., 1995). These indicators are intended to convey the most significant information in summary form, and to act as a means of communication. Examples of "land quality indicators" are workability, trafficability, leaching potential, and soil aeration. In this study the land quality indicator "transpiration ratio" ($E_{\mathrm{ratio}}$), defined as the ratio between actual and potential transpiration, was analysed for different land management types. $E_{\mathrm{ratio}}$ can be considered as an integrated parameter to express water dynamics in soils. Land quality indicators can be obtained by field observations or by simulation modelling. Field observations are very expensive and time consuming. Simulation modelling, based on soil properties resulting from different management practices, is an attractive alternative to evaluate sustainability. Well-tested simulation models are available nowadays and a large amount of techniques to quantify soil properties have been developed. However, considering field experiments or computer modelling, two major scale problems should be faced: what will be the appropriate spatial scale considering soil data and what will be the relevant time scale to express land quality indicators. A related question is the consequence of averaging soil or weather data on these indicators. The latter can be expressed as the dilemma between "average first, calculate later" vs. "calculate first, average later". For highly non-linear processes, such as soil-water interactions, one would expect a substantial difference between the two methods.

Of particular importance as well is the effect of the variability in soil parameters on calculated soil quality indicators. Many techniques are available to deal with variability in soil parameters. A generally accepted and applied methodology is based on the similar media theory of Miller and Miller (1956), combined with Monte Carlo simulations (among others, Kim and Stricker, 1996 and Hopmans and Stricker, 1989). Another methodology to describe soil heterogeneity is based on geostatistical techniques like kriging (Bouma et al., 1996). All these approaches provide valuable information but need a lot of data that is often lacking for land sustainability studies (Wagenet et al., 1991).

Variability in weather conditions should be taken into account as it is likely to have a significant influence on the land quality indicators. In field experiments, uncontrollable weather conditions determine the results, which can be a serious draw-back for short-term experiments. By using well-validated simulation models this limitation does not occur. Some possibilities are the use of one representative year, average climatic conditions, a dry and a wet year (Hopmans and Stricker, 1989) or a probability density function (Kim and Stricker, 1996). Weather data are in general easily obtainable for a long historical period.

In previous studies different management systems within one soil series were quantified by land quality indicators based on average soil properties and variability in weather conditions (Droogers and Bouma, 1996; Droogers et al., 1996). This study focuses on the impact of variability in soil characteristics and variability in weather conditions on the land quality indicator "transpiration ratio" ($E_{\text{ratio}}$) for different management types.

### *Simulation model*

Soil water dynamics are described with the well-known Richards' equation:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z}+1\right)-S(h)\right] \tag{3.1}$$

where $\theta$ denotes the soil water content (cm$^3$ cm$^{-3}$), $t$ is time (d), $h$ (cm) the soil matric head with $h < 0$, $z$ (cm) the vertical co-ordinate, taken positive upwards and $z = 0$ at land surface, $K$ the hydraulic conductivity (cm d$^{-1}$). $S$ (d$^{-1}$) represents the water uptake by plant roots (Feddes et al., 1978), defined as:

$$S(h)=\alpha(h)\frac{E_{pot}}{|z_r|} \tag{3.2}$$

with $E_{\text{pot}}$ is potential transpiration (cm d$^{-1}$), $z_r$ is rooting depth (cm), and $\alpha$ (-) is a reduction factor as function of $h$ and accounts for water deficit. Unlimited water uptake by plants was at $h > -800$ cm at low evaporative demand (1 mm d$^{-1}$) and $h > -200$ cm at high evaporative demand (5 mm d$^{-1}$). Between these points and wilting point, $h = -4000$ cm, a linear reduction was assumed. Below $h = -4000$ cm water uptake was assumed to be zero. Total actual transpiration, $E_{act}$, was calculated as the depth integral of the water uptake function $S$. A finite difference solution scheme was used to solve these equations (Vanclooster et al., 1994). Model performance in general was tested, among others, by Diels (1994) and Vanclooster (1995). Model performance for this specific case has been tested by Droogers and Bouma (1996).

# MATERIALS

## *Soils and management*

Within one soil type, a loamy, mixed, mesic Typic Fluvaquent (Soil Survey Staff, 1975), three different farm management types were selected, all located in the south-western part of the Netherlands. Two temporary grasslands, managed biodynamically (*Bio*) and conventionally (*Conv*), and one permanent grassland (*Perm*), were selected. Management has influenced the basic properties of the topsoil like organic matter, bulk density and porosity and differs significantly for the three distinguished types (Droogers et al., 1996). The selected fields are considered to be similar in the first place and differences in soils are only a result of the different management types. Evidence for this could be found in the origin of the soils, the similar texture of the fields and the identical soil properties below the topsoil (Droogers et al., 1996). For each management type one field was studied. Within each field four plots (three for *Perm*) were selected randomly and at each plot two soil profiles were sampled. From each profile undisturbed samples of 300 $cm^3$ were taken at 20, 50 and 80 cm depth for determining soil hydraulic characteristics by multistep outflow method (Van Dam et al., 1994). Additionally, undisturbed samples of 6000 $cm^3$ were taken at the same depth for measuring saturated and near-saturated conductivity by the crust method (Booltink et al., 1991). Outflow data, conductivity data and additional retention points at a matric pressure head of -1000 and -16 000 cm, were used to fit parameters for an analytical description of the retention and conductivity curves, using the program MULSTP (Van Dam et al., 1990). The well-known Mualem-VanGenuchten (Van Genuchten, 1980) equation resulted in a poor fit of the measured data. Describing the retention curve according to the VanGenuchten equation, with m = 1 and without the restriction n > 1, and the conductivity curve according to Gardner (1958), resulted in much better fits. Same conclusions were found by Vereecken et al. (1989, 1990b). Hence, the soil hydraulic characteristics are described as:

$$\theta(h) = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{1 + |\alpha h|^n} \tag{3.3}$$

$$K(h) = \frac{K_{sat}}{1 + |\beta h|^L} \tag{3.4}$$

where $\theta$ is volumetric water content ($cm^3$ $cm^{-3}$), $h$ is matric pressure head (cm), $\theta_{res}$ is residual water content ($cm^3$ $cm^{-3}$), $\theta_{sat}$ is saturated water content ($cm^3$ $cm^{-3}$), $K$ is hydraulic conductivity (cm $d^{-1}$), $K_{sat}$ is saturated hydraulic conductivity (cm $d^{-1}$), $\alpha$ ($cm^{-1}$), $\beta$ ($cm^{-1}$), $n$ (-) and $L$ (-) are fitting parameters.

For each depth the eight individual hydraulic characteristics were averaged on the basis of the matric pressure head, taking the arithmetic mean for moisture contents and geometric mean for the conductivity's:

$$\overline{\theta}(h) = \frac{\sum_{n=1}^{8} \theta_n(h)}{8} \qquad (3.5)$$

$$\overline{K}(h) = \left(\prod_{n=1}^{8} K_n(h)\right)^{\frac{1}{8}} \qquad (3.6)$$

These mean retention and conductivity curves were also fit according to eqs. 3.3 and 3.4. The individual and mean hydraulic properties for the topsoils are presented in Fig. 3.1.

### Weather conditions

Weather conditions on daily base, rainfall and potential transpiration, from 1959 to 1989 in the Netherlands were used. Variation between these 30 years was mainly restricted to the rainfall ($\mu$ = 819 mm, $\sigma$=160 mm), while potential transpiration was quite homogeneous ($\mu$ = 544 mm, $\sigma$=37 mm). The annual potential water deficit, defined as the difference between annual rainfall and annual potential transpiration, shows the highest variation ($\mu$ = 275 mm, $\sigma$=184 mm). Potential transpiration was calculated according to normal practices of the Dutch Meteorological Office (Makkink, 1960; de Bruin, 1981):

$$E_{pot} = \frac{1}{\rho_w \lambda} 0.65 \frac{s}{s+\gamma} K\downarrow \qquad (3.7)$$

where $E_{pot}$ is potential transpiration (m $s^{-1}$), $\rho_w$ is density of water (kg $m^{-3}$), $\lambda$ is latent heat of vaporisation (J $kg^{-1}$), $s$ is slope of the saturation vapour pressure curve in air (Pa $K^{-1}$), $\gamma$ is psychrometric constant (Pa $K^{-1}$), and $K\downarrow$ is global radiation (W $m^{-2}$).

### Simulations

Simulations were performed by applying the soil properties in two ways. First, by using all the measured soil properties, eight profiles per management type (six for *Perm*): the individual soil data set. Second, by using the average soil properties for each management type according to eqs. 3.5 and 3.6: the average data set.

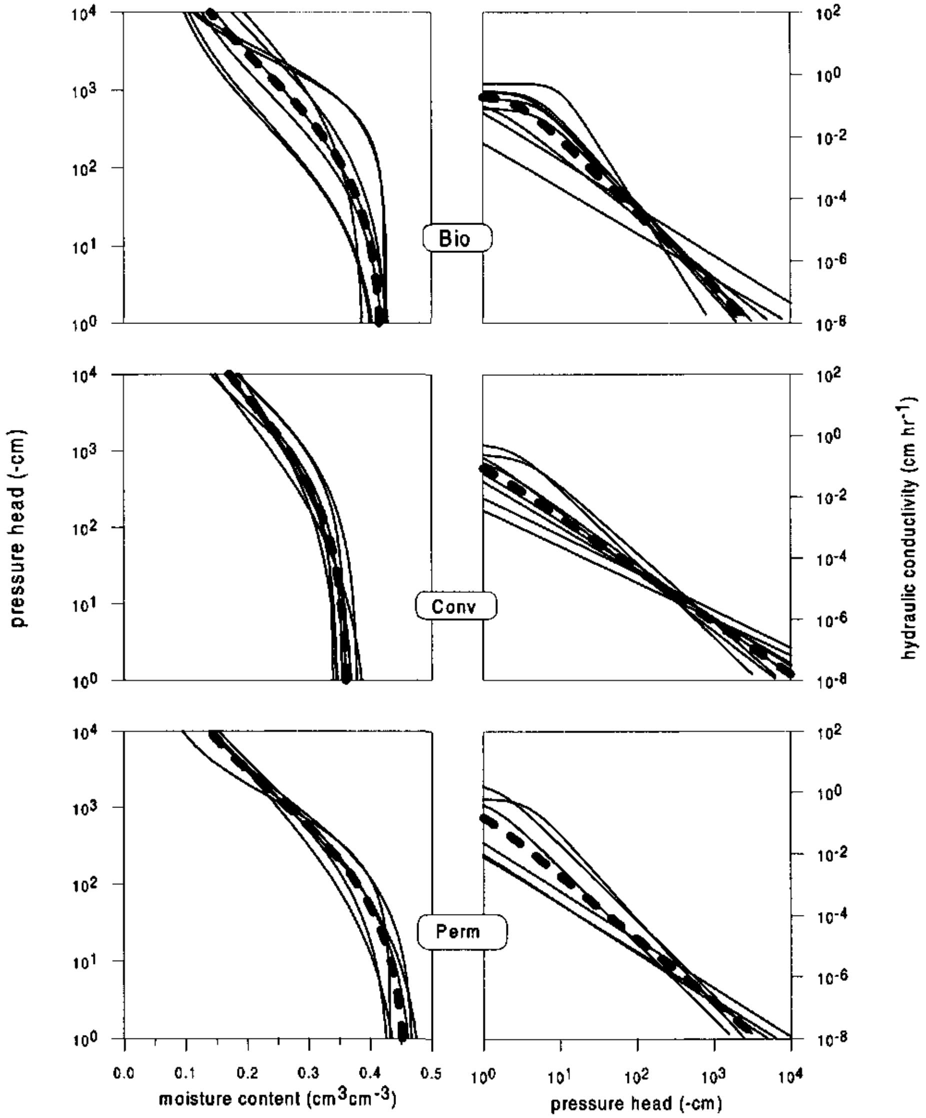


**Figure 3.1. Soil hydraulic characteristics of the topsoil for the three management types. Solid lines indicate the individual soil characteristics, eight per depth (six for *Perm*); dotted lines denote the average curves.**

These two scenarios were compared on the transpiration ratio ($E_{\mathrm{ratio}}$), defined as the ratio between the simulated annual actual transpiration ($E_{\mathrm{act}}$) and the annual potential transpiration ($E_{\mathrm{pot}}$). $E_{\mathrm{pot}}$ was calculated according to eq. 3.7. As crop a grass vegetation with a rooting depth of 20 cm was considered, covering the soil completely. The actual transpiration ($E_{\mathrm{act}}$) was simulated and is a function of the $E_{\mathrm{pot}}$ and the matric pressure head in the soil (eq. 3.2).

# RESULTS

Transpiration ratios ($E_{\mathrm{ratio}}$), given as average values for the 30 years of weather data, are shown in Table 3.1. The influence of applying the average soil characteristics for each management type rather than the individual properties, is negligible. Considering individual years, averaging the soil parameters has almost no effect on the $E_{\mathrm{ratio}}$ as well (Fig. 3.2). Similar conclusions, but for other soils and conditions, were reported by Feddes et al. (1993). Kim and Stricker (1996) concluded for the water balance of two soil types, that representative soil parameters for a sandy soil exist, but were absent for a loamy soil. However, concentrating on the $E_{\mathrm{ratio}}$ instead of the whole water balance, representative soil parameters did exist for both the sandy and the loamy soil.

**Table 3.1. Effects of averaging soil properties on the transpiration ratio ($E_{\mathrm{ratio}}$) for the three management types. *Bio* is biodynamic temporary grassland, *Conv* is conventional temporary grassland and *Perm* is permanent grassland. Hydraulic soil properties were obtained from eight soil profiles (six for *Perm*), weather conditions are from 30 years of historical data.**

| | soil: average | | | soil: individual | | |
|---|---|---|---|---|---|---|
| | $E_{\mathrm{ratio}}$ | var. | $n$ | $E_{\mathrm{ratio}}$ | var. | $n$ |
| Bio | 0.81 b | 0.012 | 30 | 0.81 b | 0.012 | 240 |
| Conv | 0.80 a | 0.011 | 30 | 0.79 a | 0.011 | 240 |
| Perm | 0.83 c | 0.013 | 30 | 0.83 c | 0.012 | 180 |

*Values followed by the same letter are not significantly different (P = 0.05) according to LSD multiple-range test.*

The three management types differ significantly in terms of the $E_{\mathrm{ratio}}$, and are highest for *Perm*, followed by *Bio* and *Conv* (Table 3.1). Variation within one year, considering the individual soil parameters, is lowest for *Conv* and highest for *Bio* and *Perm* (Fig. 3.2). Clearly, the conventional management type results in a lower soil variation but also in a lower production potential. Soil variation is higher for *Bio* and *Perm*, and also productivity, expressed as the $E_{\mathrm{ratio}}$, is higher.

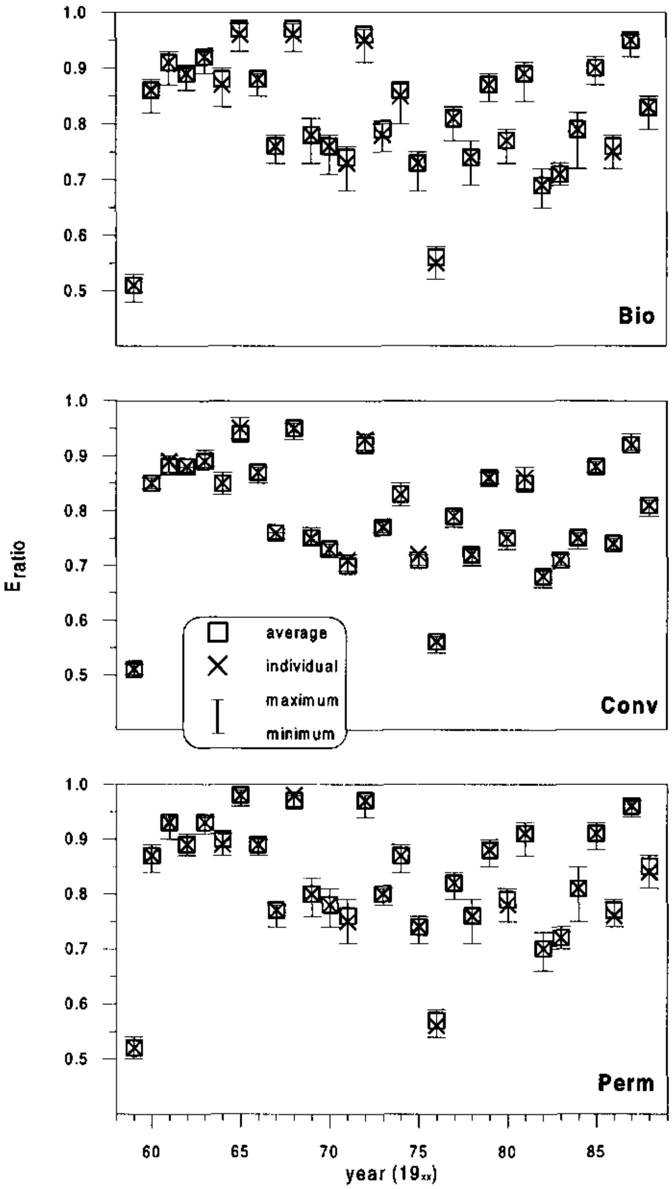


**Figure 3.2.** **$E_{ratio}$ for the average and the individual soil properties for the 30 individual years. Ranges indicates the minimum and maximum $E_{ratio}$ for the individual soil properties.**

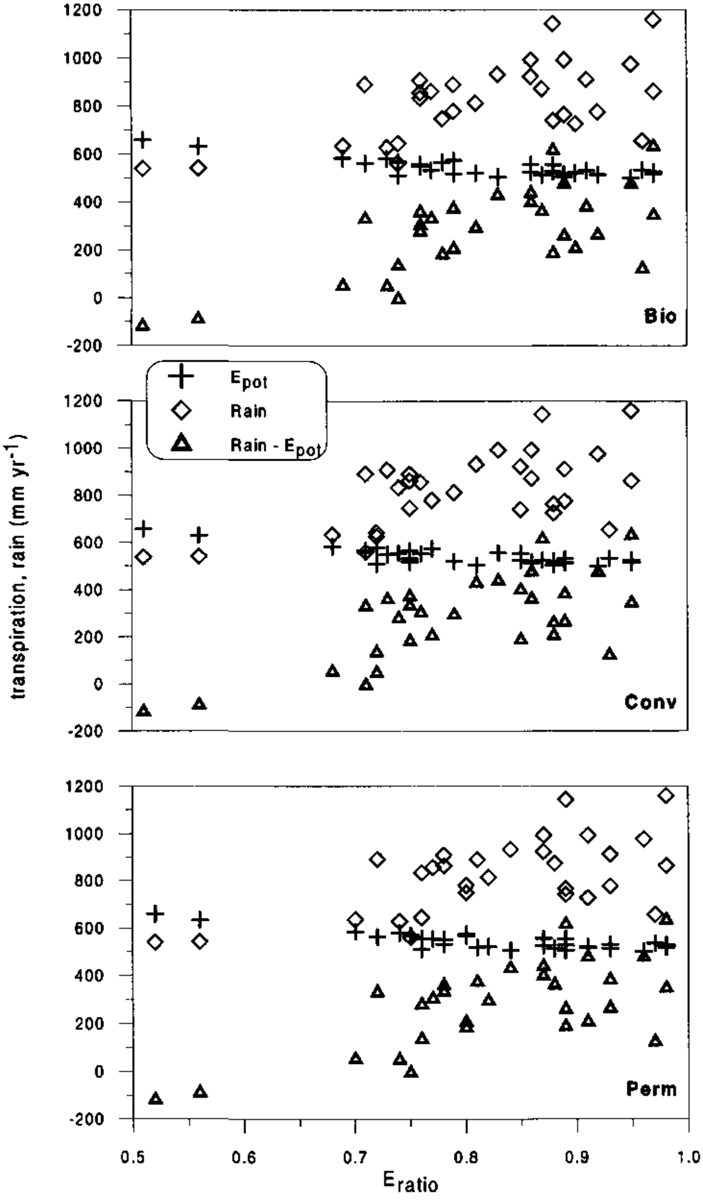


**Figure 3.3. Relation between the $E_{ratio}$ and weather conditions for the three management types.**

In stead of using a period of 30 years with weather data, one representative year or a dry and a wet year could be used. These options are only valid if there exists a correlation between the weather conditions and the $E_{ratio}$. Fig. 3.3 shows these relations between

$E_{\text{ratio}}$, precipitation, potential transpiration and annual potential water deficits. Correlations for precipitation and potential water deficits vs. $E_{\text{ratio}}$ are low. Moreover, differences in potential transpiration among the years are too small to function as distinctive feature. So, selection of a representative or a dry or a wet year based on observed weather data, will not automatically result in a representative or a low or a high $E_{\text{ratio}}$.

### Appropriate time scale

Since weather conditions have such a considerable effect, the question arises what the proper time scale should be to evaluate land quality indicators. In other words: over how many years should an experiment, in the field or by simulations, be performed to reduce the effects of unpredictable weather conditions. The results of the simulations with the historical 30 years of weather data were used to analyse this question. The 30 $E_{\text{ratio}}$ values were used to create series using the running-average method with intervals from 1 till 30. These intervals could be read as "evaluation years", the number of years an experiment is lasting. From these 30 series the minimum, maximum and variance were calculated:

$$Min(n) = Min_{i=1}^{30-(n-1)}\left[\frac{1}{n}\sum_{j=1}^{i+(n-1)} Eratio_j\right] \qquad n = 1..30 \qquad (3.8)$$

$$Max(n) = Max_{i=1}^{30-(n-1)}\left[\frac{1}{n}\sum_{j=1}^{i+(n-1)} Eratio_j\right] \qquad n = 1..30 \qquad (3.9)$$

$$Var(n) = Var_{i=1}^{30-(n-1)}\left[\frac{1}{n}\sum_{j=1}^{i+(n-1)} Eratio_j\right] \qquad n = 1..30 \qquad (3.10)$$

with *Min*, *Max*, and *Var* is respectively the minimal, maximal and variance of a series with number of evaluation years *n*.

Additionally, the differential of the variance, or in other words, the decrease in variance as function of increasing evaluated years, was calculated:

$$\Delta Var(n) = Var(n) - Var(n-1) \qquad n = 2..30 \qquad (3.11)$$

Results show that the range, defined as the difference between the minimum and maximum $E_{\text{ratio}}$, reduces as more years are considered in the analysis (left part of Fig. 3.4). Especially, the minimum $E_{\text{ratio}}$ is largely influenced by the number of evaluated years. The variance is reduced with increasing number of evaluated years (right part of Fig. 3.4). The differential of the variance (dotted line of Fig. 3.4) becomes constant after about seven evaluation years. This point indicates the time where the reduction in variance becomes linear. Somewhat arbitrary this period of seven years can be regarded as the critical period an experiment should be conducted to adequately express the effects of unpredictable weather conditions. Performing experiments over a longer period will result in a reduction of the variance, but surplus value will be questionable considering the high costs of such an experiment. Although $E_{\text{ratio}}$ is significantly different for the three management types, the variance and the differential in variance are similar.

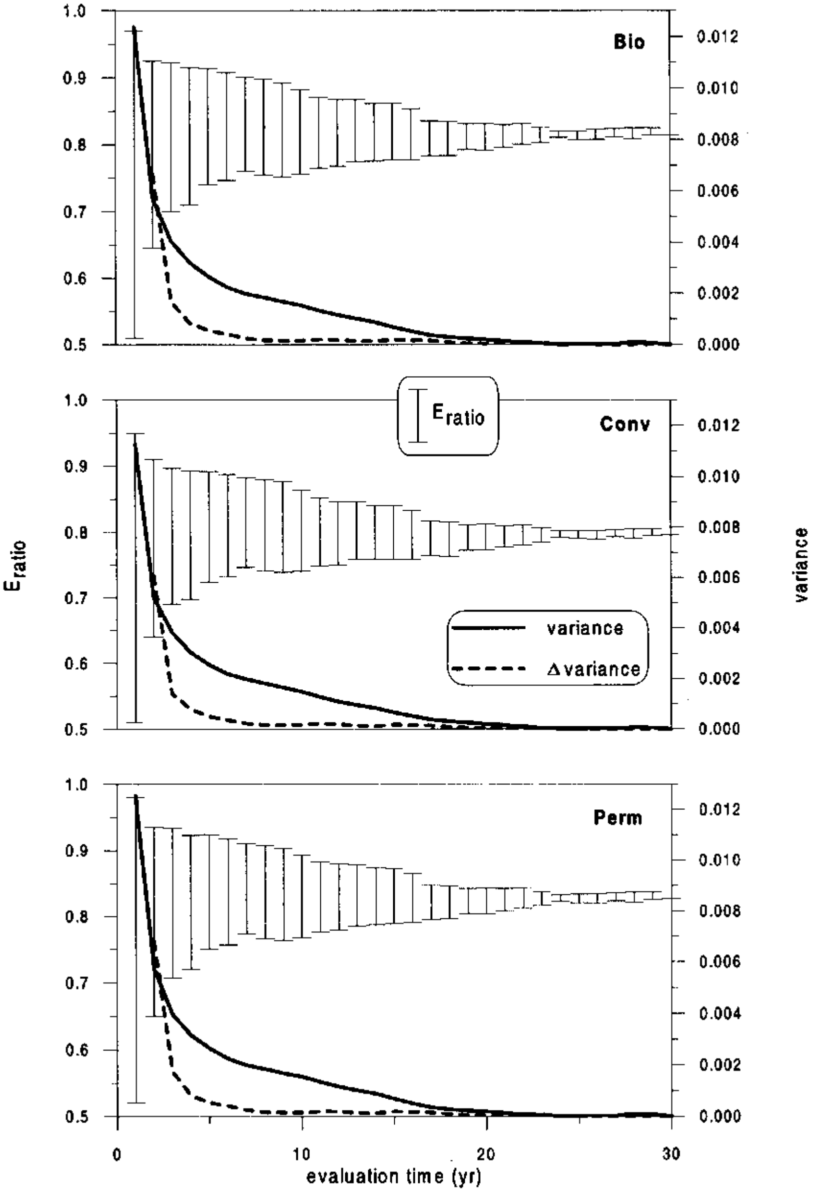


**Figure 3.4. Relation between the length of an experiment, the evaluation time, and the expected $E_{ratio}$. Range in $E_{ratio}$ denotes the minimum and maximum expected $E_{ratio}$ (left axis). Δvariance indicates the reduction in variance by increasing evaluation times (right axis).**

## DISCUSSION AND CONCLUSIONS

1. Averaging soil hydraulic parameters for a given management type in a defined soil series did not affect the simulated transpiration ratio.

2. Different management types, within one soil series, result in different transpiration ratios. Analyses based on soil types only, while ignoring applied management, provide inadequate resolution.

3. Weather data have a major impact on transpiration ratio. A sustainability analysis focused on the land quality indicator $E_{\mathrm{ratio}}$ should last at least seven years, to adequately express the effect of variable weather conditions. This means that field experiments designed to quantify the land quality indicator $E_{\mathrm{ratio}}$ are not feasible: there is no time to wait seven years to arrive at conclusions, and the costs of such a field experiment will be far too high.

## ACKNOWLEDGEMENTS

The author thanks Prof. Johan Bouma for very useful discussions and comments. This study was supported by the Netherlands Geosciences Foundation (GOA) with financial aid from the Netherlands Organization for Scientific Research (NWO). The work is part of the research program of the C. T. de Wit Graduate School of Production Ecology.

# Chapter 4

# TIME AGGREGATION OF NITROGEN LEACHING IN RELATION TO CRITICAL THRESHOLD VALUES

**Abstract** Leaching of nitrate contributes to the deterioration of groundwater and can consequently have a negative influence on the quality of our drinking-water. Critical threshold values for nitrogen leaching are established to preserve groundwater quality. A critical threshold value for nitrate leaching of 50 mg $l^{-1}$ (11.3 mg N $l^{-1}$), similar to the drinking water standard, serves as a threshold value for European countries. However, the temporal aggregation scale on which this threshold value should be considered is unknown. A well tested simulation model was used to evaluate the exceedance of the threshold value at different time aggregation levels, ranging from one day till 30 years. For three different soil structure types within one soil type and a selected fertilisation regime, the aggregated nitrogen leaching over 30 years was 11.4, 19.2 and 10.6 mg $l^{-1}$. Considering an aggregation level of one day, the critical threshold value of 11.3 mg N $l^{-1}$ was exceeded 2973, 5801 and 2556 times, respectively, for the three structure types during 30 years. By considering other time aggregation levels, a clear relation resulted between time aggregation level and the number of time elements during which the critical level was exceeded. Results strongly indicate that a critical threshold value for leaching should include an associated time-aggregation level.

## INTRODUCTION

There is a growing awareness that leaching of agro-chemicals, biocides as well as fertilisers, has a negative influence on the quality of our drinking-water. It is also widely accepted that clean drinking-water can better be achieved by reducing leaching of chemicals to the groundwater, than by removing hazardous chemicals from the drinking-water itself. Therefore, a strong political and legislative pressure exists to reduce leaching and to establish threshold values that may not be exceeded. For example, nitrate concentrations in drinking-water higher than 50 mg $l^{-1}$ are considered to be dangerous for public health. This 50 mg $l^{-1}$ nitrate, equivalent with 11.3 mg N $l^{-1}$, will therefore serve as a threshold value for N-leaching to the groundwater. Integrated N management in relation to N-leaching and groundwater quality is an important research topic (Follett and Wieringa, 1995). The number of papers describing relations between N fertiliser management and N-leaching is very large. Analyses are often based on field measurements, but as this implies extensive analytical and measuring procedures, the use of well-tested simulation models is not only attractive but imperative (Huwe and Totsche, 1995).

However, two scale issues are essential in the discussion about critical threshold values for leaching, which have, so far, hardly been considered. First, what is the spatial aggregation level of this threshold value: a point, a parcel, a farm, a region, or even a country? Second, what is the appropriate temporal aggregation level: a day, a month, a season, or a year? It is clear that low aggregation levels, spatial as well as temporal, are more restrictive than higher levels. For example, never exceeding a certain threshold value on any particular day, is much more restrictive than aggregating leaching over an entire year. It is also more restrictive to maintain this threshold value on any individual spot, than to aggregate and apply it for a complete watershed.

Considering the spatial scale, there seems to be a tendency, not scientifically based, to focus on the farm level. The main reason for this is that an input-output balance of nitrogen can be made and controlled rather easily at this spatial scale level. Discussions about this spatial aggregation level are not considered here, but can be found elsewhere. For example, Porter (1995) reported great variability of N-leaching at a very small scale of some $m^2$. Also at a regional scale (hundreds or thousands of $km^2$) variability is large and N-leaching often occurs in well-defined "hot-spot" areas (Schaffer et al., 1995). Verhagen et al. (1995), studied variability at field scale and concluded that, because of high spatial variability, site-specific management appeared to be attractive for a more efficient natural resources use.

This study focuses on the temporal aggregation level, with the main question: "what will be the effect of different time aggregation levels on whether a critical threshold value for N-leaching is exceeded?". In other words: "Is the distinction of a threshold value meaningful if no time aggregation level is associated with it?". As mentioned before, the threshold value is considered to be similar to the drinking-water standard. Of course, mixing of groundwater below the N-leaching source before reaching the drinking well is very likely to cause dilution of N. The drinking-water standard, to be applied at the level of the groundwater surface, represents therefore a very rigid threshold.

For one soil series in the Netherlands, a loamy Fluvaquent, hydraulic characteristics of three different soil structure types, were used to calculate nitrogen leaching to the groundwater. This was done by using a well tested and validated deterministic simulation model, based on Richards' equation. Results of the nitrogen leaching were aggregated over different time segments ranging from one day till 30 years.

In summary, the objectives of this study were to make a preliminary analysis on the relationship between the critical threshold value for N-leaching and its temporal aggregation level of the threshold value.

## MATERIALS AND METHODS

### *Soils*

Differences in soil structure, even within one soil type, can behave quite differently (e.g. Bouma, 1994) and should therefore be taken into account. Within one soil type, a mixed mesic typic Fluvaquent (Soil Survey Staff, 1975), three soil structure types were selected. These different structure types were the result of different management types and are denoted as *Bio* (biodynamic), *Conv* (conventional), and *Perm* (permanent grassland). No chemical fertilizer or chemical crop protection was utilized for *Bio*, but a favourable crop rotation and organic fertilizer was used to maintain soil quality. *Conv* did use agrochemicals and organic fertilzer was hardly applied. However, soil tillage practices for *Bio* and *Conv* were similar and consisted of ploughing in autumn till a depth of 25-30 cm as the main tillage activity. Field *Perm* had been permanently under grassland since 1947, representing a soil structure with a more or less natural character. These three structure types have a significantly different behaviour in terms of moisture regimes, nitrogen dynamics, crop growth, trafficability, water-accessibility, etc. So, instead of concentrating on one "representative" profile, a range of structure types is considered. Detailed descriptions of these structure types can be found elsewhere (Droogers et al., 1996). Some basic soil parameters are presented in Table 4.1.

**Table 4.1. Basic properties of the topsoil, 10-30 cm, for the three soil structure types.**

| | Bulk density | | Organic matter | | Porosity | |
|---|---|---|---|---|---|---|
| | avg. | std. | avg. | std. | avg. | std. |
| | — Mg $m^{-3}$ — | | —— % —— | | — $m^3$ $m^{-3}$ — | |
| Bio | 1.47 b | 0.065 | 3.3 b | 0.59 | 0.42 b | 0.015 |
| Conv | 1.68 c | 0.061 | 1.7 a | 0.05 | 0.36 a | 0.021 |
| Perm | 1.38 a | 0.109 | 5.0 c | 0.57 | 0.46 c | 0.023 |

*Differences are significant at P = 0.05 if followed by different letters.*

### Simulations

A deterministic, mechanistic, numerical simulation model was used which consists of the following modules: moisture, solutes, nitrogen, organic matter, heat and cropgrowth (Vanclooster et al., 1994). The main body of this model is the soil water dynamics module which was based on the well known Swatre model (Feddes et al., 1978). A finite difference approach was used to solve Richards' equation and hydraulic characteristics were described with the Van Genuchten equations (Van Genuchten, 1980) with some small modifications as described by Droogers and Bouma (1996). More detailed information about the simulation model, input data and boundary conditions are beyond the scope of this paper, but can also be found in Droogers and Bouma (1996). General model performance was already tested extensively (among others, Diels, 1994; Vanclooster, 1995), and for these particular soils by Droogers and Bouma (1996). Decomposition of organic matter (mineralisation) can have a significant influence on the N balance and thus on N-leaching. For this study this mineralisation was assumed to be zero, to emphasise only the inorganic N behaviour. Analyses including these organic matter dynamics for the three soil structure types can be found in Droogers and Bouma (1997).

Simulations for the three soil structure types were performed assuming potatoes as a crop. Although *Perm* was permanent under grassland, this soil structure type could be considered representing a management practices with minimum tillage. A N fertiliser application of 200 kg $ha^{-1}$ was considered following normal practices for the three soil structures. In order to take into account variation in weather conditions, simulations were made by using historical daily weather data, including rainfall, for a continuous period of 30 years (1959-1988). Although potatoes cannot, of course, be grown for 30 years on the same field, these 30 years were only used here to obtain a distribution of yields as a function of differences in weather conditions. For each individual year a planting date of April 15th was assumed and fertilisers were applied on the same date.

The term leaching is ill-defined and involves both quantity and concentration. In this study the term leaching is exclusively used for concentration (mg $l^{-1}$). Therefore, the simulated daily water fluxes ($m^3$ $m^{-2}$) and the daily N fluxes (g $m^{-2}$) are converted to concentrations of N-leaching (mg $l^{-1}$). These water and N fluxes are considered at a depth equal to the groundwater depth, which fluctuated from 130 cm in summer till 90 cm in winter.

### Aggregation

First the average N-leaching during one year was determined by using the 30 years of simulations. These 30 years resulted in a vector of 10950 (30 years x 365 days) elements with daily water fluxes and a similar vector containing nitrogen fluxes. The average pattern of N-leaching during one year was generated by aggregating the 30 years on daily base:

$$NL_d = \frac{\sum_{j=1}^{30} Nflx_{d+365(j-1)}}{\sum_{j=1}^{30} Wflx_{d+365(j-1)}} \qquad d = 1..365 \qquad (4.1)$$

where $NL$ is nitrogen leaching (mg $l^{-1}$), $Nflx$ is nitrogen flux (g $m^{-2}$), $Wflx$ is water flux ($m^3$ $m^2$), $d$ is day of the year and $j$ denotes the year number.

In addition to this average annual course, the effect of aggregation of the N-leaching over a certain time interval was analysed as well. Again the results of the daily water fluxes and N fluxes of the 30 years were used. In order to take into account the annual course in N-leaching, aggregation should be performed on levels that are dividers of one year. To obtain a reasonable amount of aggregation levels, years were assumed to have 360 days in stead of 365 days.

$$NL_i = \frac{\sum_{j=1}^{T} Nflx_{j+T(i-1)}}{\sum_{j=1}^{T} Wflx_{j+T(i-1)}} \qquad i = 1...(30 \cdot 360)/T \qquad (4.2)$$

where i is interval of aggregation, T is aggregation level (d) defined as the dividers of 360. From each aggregation level T, a number of T series can be made. Taking for example an aggregation level of 2 days the following series can be made: 1+2, 3+4, 5+6, ... and 2+3, 4+5, 6+7, ... Each series was analysed in terms of the number of intervals with a higher N-leaching than 11.3 mg $l^{-1}$.

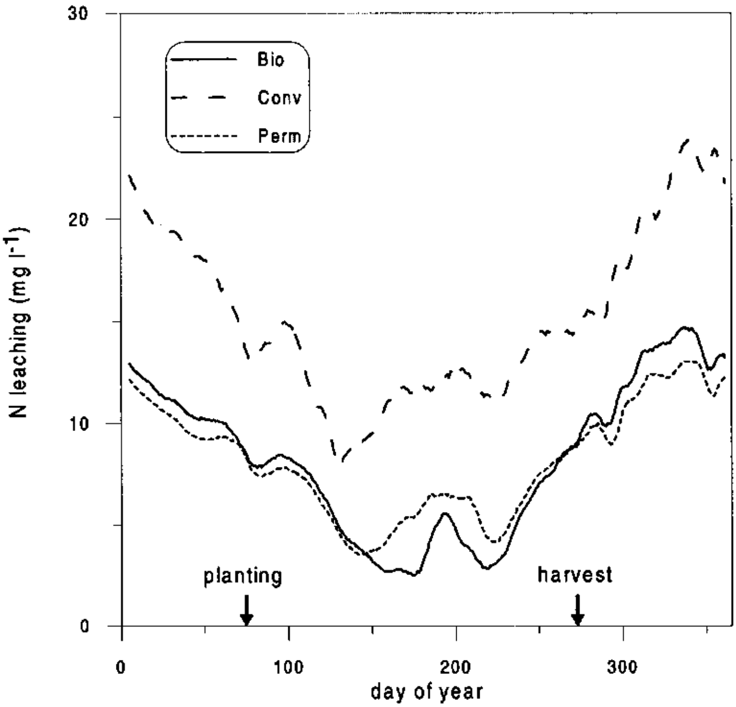


**Figure 4.1. Daily course of N-leaching, expressed as N concentration in water which enters the groundwater, for the three different soil structure types. Results were obtained by averaging simulated N-leaching for each day for a thirty years period. Data are plotted as running averages with a window width of 9 days.**

## RESULTS

The daily N-leaching, as stated before expressed as N concentrations in the water that enters the groundwater, averaged by using the 30 years of simulations, shows a clear annual course (Fig. 4.1). After planting, N-leaching decreases despite the application of N at the same time. The main reason for this decrease is the low amount of rainfall in spring and the uptake of water and N by the plant. The increase in N-leaching around day 200 is the result of some convective rainfall on the relatively dry soil. The water flux towards the groundwater is not very high, which leads to a short, relatively high, N concentration peak. Much rainfall occurs during the last 100 days of the year, inducing high N-leaching. By the end of the year a substantial amount of N is being leached, resulting in a decrease in N-leaching at the beginning of the next year. Thus, this is a kind of "steady state" situation.

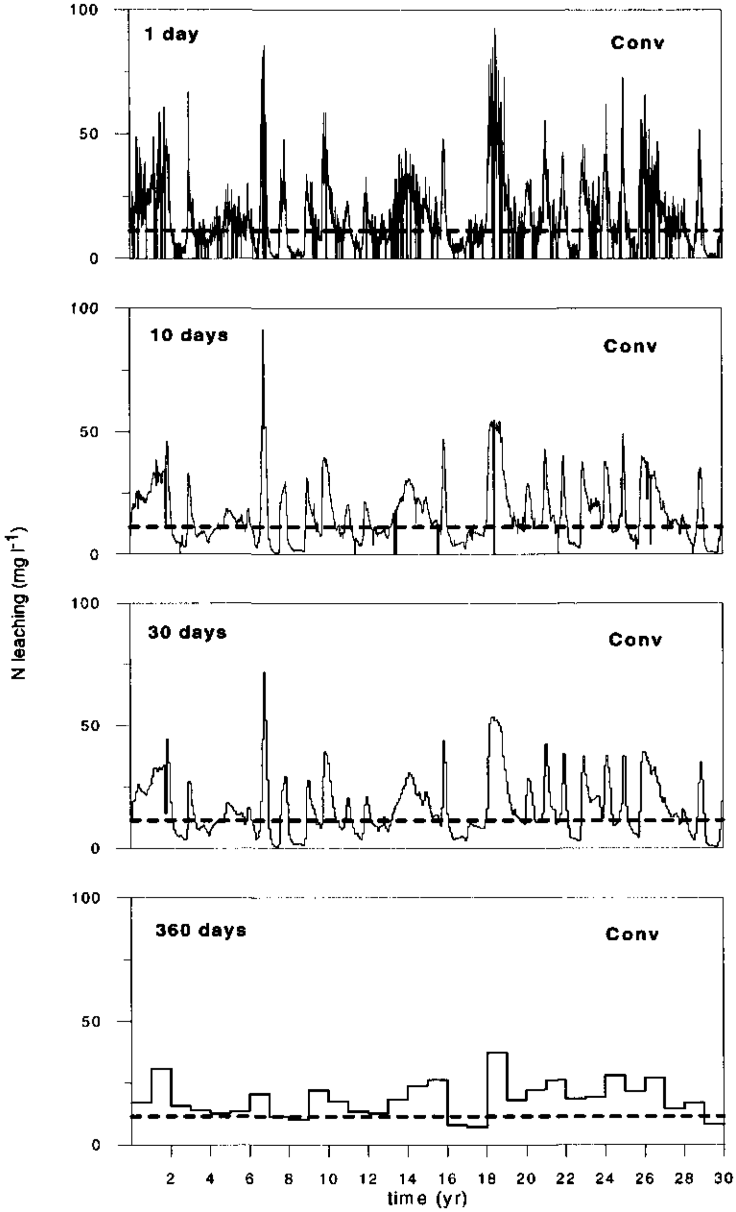


**Figure 4.2a.** N-leaching for the 30 year-period aggregated over 1, 10, 30 and 360 days for *Conv*. Dotted lines indicate the critical threshold value of 11.3 mg $l^{-1}$.

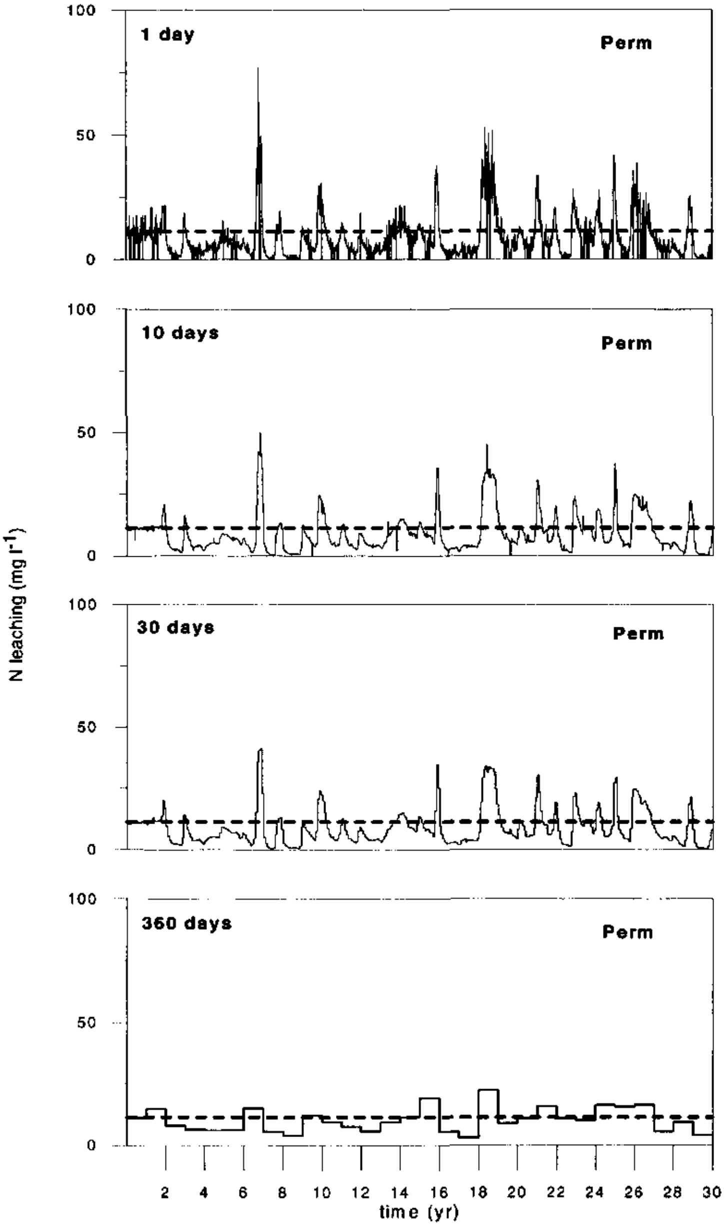


**Figure 4.2b. N-leaching for the 30 year-period aggregated over 1, 10, 30 and 360 days for *Perm*. Dotted lines indicate the critical threshold value of 11.3 mg $l^{-1}$.**

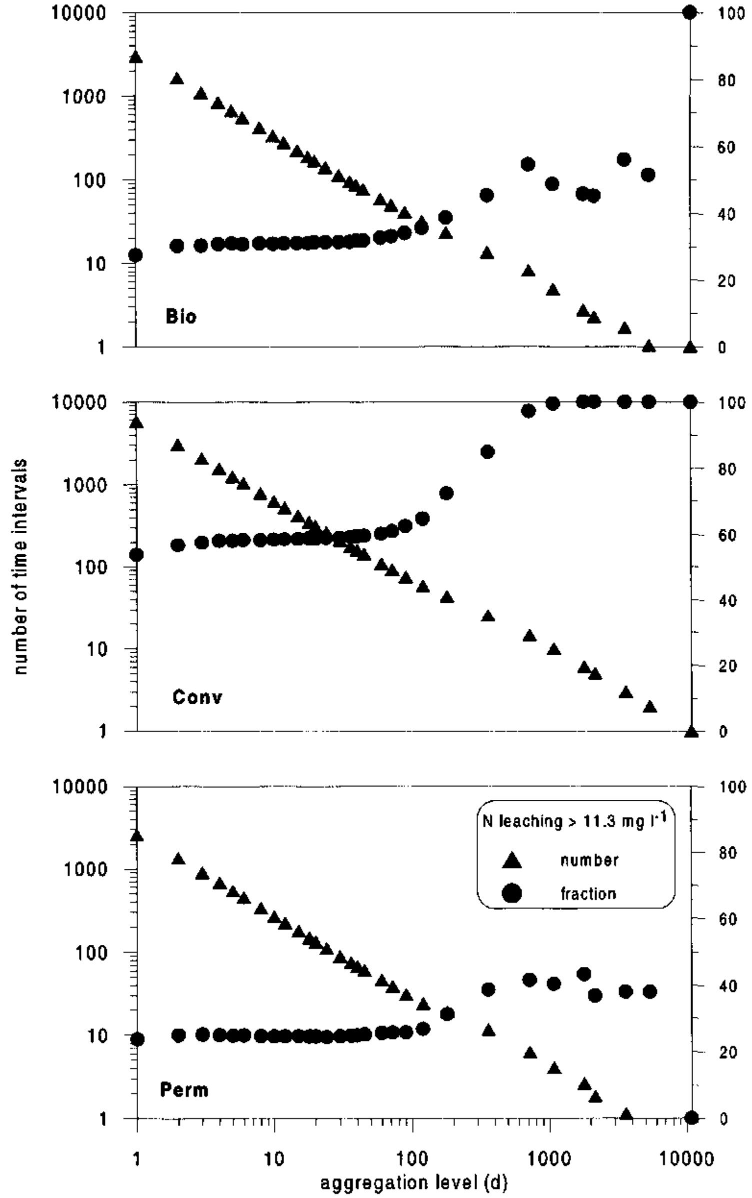


Figure 4.3. Relation between aggregation level and N-leaching for the three soil structure types. Left y-axis and triangle indicate the number of intervals exceeding the critical threshold value of 11.3 mg N $l^{-1}$. Right y-axis and circles show the fraction of intervals when this critical threshold value was exceeded.

**Table 4.2. Summary results of the simulations with 30 years of climatic data.**

| | Whole year | | | Growing season | | | Non-growing season | | |
|---|---|---|---|---|---|---|---|---|---|
| | Water leaching | N-leaching | | Water leaching | N-leaching | | Water leaching | N-leaching | |
| | mm | kg ha$^{-1}$ | mg l$^{-1}$ | mm | kg ha$^{-1}$ | mg l$^{-1}$ | mm | kg ha$^{-1}$ | mg l$^{-1}$ |
| Bio | 427 | 48.7 | 11.4 | 137 | 10.2 | 7.5 | 290 | 38.5 | 13.3 |
| Conv | 394 | 75.6 | 19.2 | 114 | 14.8 | 12.9 | 280 | 60.8 | 21.8 |
| Perm | 409 | 43.4 | 10.6 | 125 | 8.9 | 7.1 | 284 | 34.5 | 12.1 |

Summary statistics from the 30 years of simulation show a substantial difference among the three soil structure types (Table 4.2). Only *Perm* has a lower N-leaching than the critical 11.3 mg l$^{-1}$, while *Bio* is very close to this critical level. However, these results were based on aggregating 30 years and do not guarantee that for each individual year *Perm* is below the threshold value. Neither does this result say anything about exceedance on a daily base. For different aggregation levels, the N-leaching during these 30 years are plotted for the two contrasting structure types *Conv* and *Perm* (Fig. 4.2). Table 4.3 shows for some aggregation levels the exceedance of the critical N-leaching. As expected, smaller aggregation levels result in a higher number of time elements where the critical level is exceeded. Considering the aggregation level of 30 years *Perm* is within the critical threshold value while *Bio* is exceeding this level. However, taking one year as the aggregation level, differences between *Perm* and *Bio* are small: *Perm* exceeds the critical level about 12 times and *Bio* about 14 times.

**Table 4.3. Exceeding a critical N-leaching of 11.3 mg l$^{-1}$ as function of the time aggregation level for the three structure types.**

| Time aggregation level | Intervals | Bio | | Conv | | Perm | |
|---|---|---|---|---|---|---|---|
| | n | n | % | n | % | n | % |
| day | 10800 | 2973.0 | 28 | 5801.0 | 54 | 2556.0 | 24 |
| 10 days | 1080 | 333.9 | 31 | 630.3 | 58 | 265.7 | 25 |
| month | 360 | 113.0 | 31 | 212.3 | 59 | 88.5 | 25 |
| year | 30 | 13.6 | 45 | 25.5 | 85 | 11.6 | 39 |
| 30 years | 1 | 1.0 | 100 | 1.0 | 100 | 0.0 | 0 |

The relation between aggregation level and N-leaching was extended to 30 aggregation levels, ranging from 1 day until 30 years (Fig. 4.3, triangles, left Y-axis). A clear double-log relationship exists between aggregation level and number of time elements where the critical N-leaching is exceeded ($R^2$ higher than 0.99 for all structure types). It seems obvious that at smaller aggregation levels a higher number of exceedance can be expected because more time levels exist. However, this points exactly to the relevance of this study: a critical N-leaching without indication of aggregation level is meaningless.

Concentrating on the percentage of time levels where the critical N-leaching is exceeded, instead of the absolute numbers, the three soil structures show different behaviour (Fig. 4.3, circles, right Y-axis). Percentage of exceedance for *Bio* is fairly constant for aggregation levels smaller than 50 days. Higher aggregation levels for *Bio* result in increasing exceedance percentage till 100% at an aggregation level of 30 years.

*Conv* shows also a constant percentage of exceedance of N-leaching until an aggregation level of 50 days, but at a level of about 60%, instead of the 30% obsereved for *Bio*. For *Conv*, aggregation levels higher than three years (1080 days) all have an exceedance of 100%. For *Perm*, aggregation levels lower than about 50 days are also at a constant level of about 25%. Higher aggregation levels show no clear trend and did not exceed 45%.

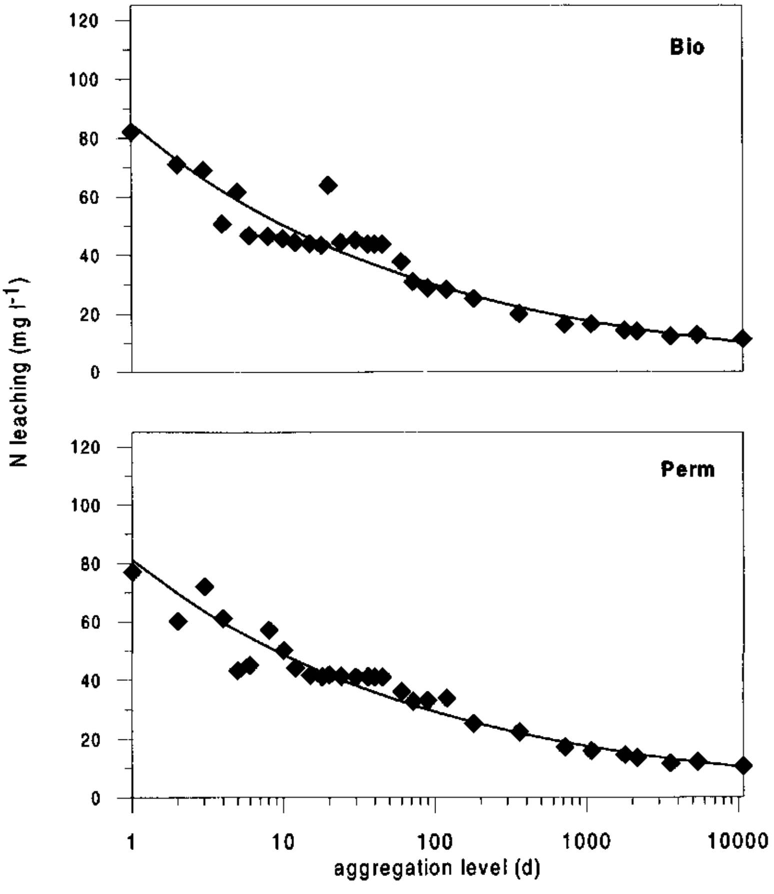


**Figure 4.4. Critical values for N-leaching at different aggregation levels which are equivalent to a threshold value of 11.3 mg N $l^{-1}$ at an aggregation level of 30 years.**

Taking the results of the highest aggregation level (30 years) as a reference, we may assume that *Perm* as well as *Bio* are (almost) acceptable according to the critical N-leaching of 11.3 mg $l^{-1}$. What will then be the critical threshold value of N-leaching for other aggregation levels? For each aggregation level a threshold value for N-leaching was determined which was not exceeded at that aggregation level. A plot of these data

(Fig. 4.4) shows a log-log relationship with $R^2$ of 0.96 and 0.95 for *Bio* (eq. 4.3) and *Perm* (eq. 4.4):

$$\ln(CNL) = -0.227 \ln(AL) + 4.44 \tag{4.3}$$

$$\ln(CNL) = -0.222 \ln(AL) + 4.40 \tag{4.4}$$

where *CNL* is critical nitrogen leaching (mg $l^{-1}$) and *AL* is aggregation level (d). Using these almost similar regressions, and assuming the aggregation level of 30 years as reference, yielded to a critical threshold value for N-leaching on a yearly base of 22 mg $l^{-1}$ and on a daily base of about 80 mg $l^{-1}$.

## DISCUSSION AND CONCLUSIONS

The presented results strongly indicate that a critical threshold value for leaching is meaningless without an associated temporal aggregation level. What the appropriate aggregation level should be, is not clear. A logical selection will have to be based on the travel time from the groundwater below the considered area to a drinking well. The methodology described (Fig. 4.4 and Eq. 4.3 and 4.4) also gives the opportunity to transform threshold values from one time-aggregation level to another one, preserving the same restrictions at the drinking well.

The results also show that different soil structures, formed by different farm management types, in an identical soil type behave significantly different in terms of N-leaching, even with identical fertilising practices. This implies that regulations based on representative soil properties for a soil type, may lead to highly variable, unrepresentative results. This can lead to threshold values which are too restrictive for some structure types, but also to values that do not adequately protect the drinking water for other structure types.

The results presented are valid for the considered soils and the defined conditions in terms of crop, weather and fertiliser application. The methodology can, of course, be easily applied for other soils, conditions and drinking water standards.

## ACKNOWLEDGEMENTS

The author thanks Johan Bouma and Jan Verhagen for useful discussions and comments. This study was supported by the Netherlands Geosciences Foundation (GOA) with financial aid from the Netherlands Organization for Scientific Research (NWO). The work is part of the research program of the C. T. de Wit Graduate School of Production Ecology.

# Chapter 5

# DESCRIBING MACRO-POROSITY DERIVED FROM STAINING PATTERNS UNDER FIELD CONDITIONS

**Abstract** Macro-porosity influences the dynamics of water and dissolved solutes in the soil. Size, shape and continuity of macro-pores is affected by applied soil management. In this study, dye staining techniques, followed by digital image processing, are used to quantify macro-porosity under field conditions in a short time at low cost. We compared 17 macro-porosity parameters, on 55 staining patterns from three fields with different soil management types at five depths, within one soil type. Factor analysis indicates that five factors explain 95% of the variation. The first factor equals the "total quantity", and was similar for the three fields, but showed significantly lower values with increasing depths. The second factor is the "individual pore quantity", and the third factor the "shape" of the pores. Both factors were influenced by soil management. Factor four and five were equal to the range and the nugget of the indicator variogram, respectively. We concluded that the most appropriate parameters to quantify staining patterns in an explanatory analysis are the number of pores, the average area per pore and the pore-shape, whereas the best parameter to quantify staining patterns with only one characteristic is the fractal dimension $D_s$.

## INTRODUCTION

Management practices have a considerable effect on soil structure and consequently on soil quality and the overall sustainability of the agricultural production system (Bouma, 1994). Especially macro-porosity can have a substantial influence on the dynamics of water and solutes in soils and can cause an anisotropic flow system, known as the "bypass flow". The bypass flow is defined as "the flow of water through a system of large pores that allows fast flow velocities and bypasses the unsaturated zone" (Beven and Germann, 1982). The process of bypass flow is effected by the number, size, shape and continuity of macro-pores. Many techniques are available to quantify this macro-porosity such as scanning methods (e.g. Heijs et al., 1995), break-through curves by tracer experiments (e.g. Bouma and Anderson, 1977), and dye staining (e.g. Bouma and Dekker, 1978). Especially the staining technique, combined with digital identification and processing methods, has many advantages. It is relatively fast and costs are low. It can be considered as a technique between the complex and fundamental scanning methods and the empirical break-through methods. Measurements can be easily performed directly in the field, without the necessity of taking samples for laboratory analysis. Moreover, the observed macro-pores from these dye staining techniques do not include all the macro-pores but identify only those pores that are connected with the infiltration surface: the continuous pores. Especially these continuous macro-pores are of relevance regarding the process of bypass flow.

The obtained macro-porosity characteristics can be used successfully as a descriptive method to compare effects of soil management on soil structure (e.g. Cattle et al., 1994).

But parameters can also be used as input for simulation models, especially to describe heterogeneous flow patterns (e.g. Booltink, 1994).

Although many papers have been published describing experiments using dye staining, there seems to be no generally accepted standard to quantify these staining patterns. We concentrate here only on the quantitative parameters, which become increasingly available as a result of the progress in digital techniques. These quantitative parameters can be categorised into basic parameters like number of pores, area, perimeter, and into more complex expressions like fractal dimensions and parameters derived from spatial statistics. Parameters for staining patterns can also be distinguished on the object they describe: the individual pores, or the pattern as a whole. For example, the ratio between area and perimeter can be used to distinguish individual pores in terms of vertical cracks or horizontal pedfaces (Bouma et al., 1977). Descriptions for the pattern as a whole can be relatively easily obtained by averaging or adding the values of all the individual pores in a pattern, e.g. the total area of stained pores or the average size of all the pores. On the other hand parameters can be more comprehensive including the spatial distribution of pores (e.g. Stein et al., 1997).

This paper concentrates on the evaluation and comparison of parameters for macro-porosity focusing on the following questions. Are different parameters for macro-porosity related to each other? Are complex parameters more effective in describing macro-porosity than straight-forward techniques? Which parameters are most effective to describe effects of different management practices on the macro-porosity of the soil? To analyze these questions, a comprehensive dataset has been collected on a loamy Fluvaquent in the Netherlands. Different parameters for macro-porosity, ranging from basic to complex, were obtained on these patterns, and compared and evaluated on their capability to quantify differences in macro-porosity.

**Table 5.1. Basic properties of the topsoil, 10-30 cm, for the three fields and their corresponding management types.**

| Field | Management | Bulk density | | Organic matter | | Porosity | |
|---|---|---|---|---|---|---|---|
| | | avg. | std. | avg. | std. | avg. | std. |
| | | — Mg $m^{-3}$ — | | —— % —— | | — $m^3$ $m^{-3}$ — | |
| Bio | biodynamic, temporary grassland | 1.47 b | 0.065 | 3.3 b | 0.59 | 0.42 b | 0.015 |
| Conv | conventional, temporary grassland | 1.68 c | 0.061 | 1.7 a | 0.05 | 0.36 a | 0.021 |
| Perm | conventional, permanent grassland | 1.38 a | 0.109 | 5.0 c | 0.57 | 0.46 c | 0.023 |

*Differences are significant at P = 0.05 if followed by different letters.*

# MATERIALS AND METHODS

## *Soils and management*

For a loamy Fluvaquent (Soil Survey Staff, 1975) in the South-Western part of the Netherlands, three fields with different management types were selected. These soils are considered to be prime agricultural land. Field *Bio* has been managed according to biodynamic principles, which means that no artificial agro-chemicals have been used. Organic fertiliser and nitrogen fixation crops like clover are used to fulfil the nutrient demand of the crops. The field has been under temporary grassland for two years. The second field, *Conv*, was also under temporary grassland, but this field for three years. Management could be defined as conventional. The third field, *Perm*, was a permanent grassland which has been used as pasture for about 80 years. Basic soil properties can be found in Table 5.1. More detailed description of soils and management practices can be found elsewhere (Droogers et al., 1996).

## *Measurements*

On each field four plots, three for *Perm*, were randomly selected. At each plot infiltration of water with methylene blue was performed using a cylindrical ring with diameter of 32 cm. Methylene blue will be absorbed by the soil, which visualises the flow pathways of the water (Bouma and Dekker, 1978). After the infiltration, horizontal planes were excavated at depths of 5, 10, 20, 30 and 40 cm below ground surface. Each horizontal plane was photographed.

## *Image processing*

From the 55 slides (four plots at *Bio* and *Conv*, three plots at *Perm*, five depths) a circle with diameter of 30 cm was used for further analyses. Patterns were scanned as grid files with gridsizes of 330 μm for *Bio* and *Perm* and 440 μm for *Conv*. Differences in gridsizes were due to a slightly different height during photographing of the planes. A supervised classification was performed to define the stained areas. A combined dilate and erode filter technique (PSP, 1996) was used to clarify the patterns, followed by conversion into polygons. The inside of pores with only stained borders were marked as stained during this process. Although some pores might have been cut off by the sampling frame which could result in an error when estimating the parameters, Hatano et al. (1992) concluded that these border effects could be neglected if the patterns were not almost entirely stained.

**Table 5.2. The 17 applied parameters to describe the staining patterns. n is total number of pores in the entire pattern, $A_{cross}$ is area of the cross-section (cm$^2$), $F$ is Feret diameter (cm), $I$ is number of squares with one or more pores inside, $r$ is square size (cm), $c$ is a constant, and subscript $i$ denotes the individual pores.**

| | symbol | definition | | short description |
|---|---|---|---|---|
| **Size** | | | | |
| | $N$ | $\frac{n}{A_{cross}}$ | cm$^{-2}$ | number of pores |
| | $A$ | $\frac{1}{A_{cross}}\sum_{i=1}^{n} A_i$ | cm$^2$ cm$^{-2}$ | total pore area |
| | $\overline{A}_{por}$ | $\frac{A}{N}$ | cm$^2$ | average area per pore |
| | $Pe$ | $\frac{1}{A_{cross}}\sum_{i=1}^{n} Pe_i$ | cm cm$^{-2}$ | total perimeter |
| | $\overline{Pe}_{por}$ | $\frac{Pe}{N}$ | cm | average perimeter per pore |
| | $CPe$ | $\frac{1}{A_{cross}}\sum_{i=1}^{n}\left[\frac{\pi}{8}\sum_{j=1}^{8} F_j\right]_i$ | cm cm$^{-2}$ | total convex perimeter |
| | $\overline{CPe}_{por}$ | $\frac{CPe}{N}$ | cm | average convex perimeter per pore |
| **Shape** | | | | |
| | $S$ | $\frac{1}{n}\sum_{i=1}^{n}\frac{Pe_i}{\sqrt{4\pi A_i}}$ | - | shape |
| | $CS$ | $\frac{1}{n}\sum_{i=1}^{n}\frac{CP_i}{\sqrt{4\pi A_i}}$ | - | convex shape |
| | $D_s$ | $\log I(r) = -D_s \log(r) + c$ | - | shape fractal dimension |
| | $D_{pe}$ | $\log A_i = -D_{pe} \log Pe_i + c$ | - | smoothness fractal dimension |
| **Distribution** | | | | |
| | *Dist05* | see text | % | % of soil within 0.5 cm of a pore |
| | *Dist10* | see text | % | % of soil within 1.0 cm of a pore |
| | *Dist20* | see text | % | % of soil within 2.0 cm of a pore |
| | *Range* | see text | cm | distance up to which a spatial dependency exists |
| | *Nugget* | see text | - | small scale variability |
| | *Sill* | see text | - | large scale variability |

# THEORY

A total of 17 parameters to describe macro-porosity were selected to be evaluated, ranging from more or less "basic" to "advanced" parameters. Table 5.2 gives an overview of the used parameters with their definition and categorisation of the characteristic they describe. These characteristics are related to the property the parameter applies to: the size, the shape, or the spatial distribution. The total area of macro-pores in a staining pattern is an example of a size parameter. Pores can also differ in their shape, such as vughs, planes and channels (Ringrose-Voase and Bullock, 84). Besides size and shape, the distribution of the pores should be described. This can be done qualitative in terms of regular, clustered, random, or quantitative using spatial statistical parameters. However, some parameters are not strictly related to only size, shape or spatial distribution. For example, the perimeter is in principle a size characteristic, but it is also related to the shape of an object. Also the distribution parameters might be related to the size as well as to the shape of a pattern.

## *Size parameters*

The size parameters are mainly "basic" parameters. They can be expressed for individual pores as well as for the entire pattern. Because this study focuses on the description of a pattern as a whole, parameters related to individual pores, area ($A_i$), perimeter ($Pe_i$) and convex perimeter ($CPe_i$), have been averaged in order to characterise the total pattern (Table 5.2). *CPe* is a reference diameter for irregular objects, being the smallest convex figure that can be constructed around a pore (Ringrose-Voase and Bullock, 1984). Eight Feret diameters have been used, equally distributed around the pore. The Feret diameter is the distance between two parallel lines that enclose an object.

## *Shape parameters*

Four different shape parameters have been applied that are in principle size-independent parameters (Ringrose-Voase and Bullock, 1984). The shape *S* is a parameter for the small irregularity of a pore. In other words, the roughness of the boundary of the pore. Related to *S*, convex shape *CS* is a size-independent expression for irregularity. But, using *CPe* instead of *Pe*, an expression for the large irregularity of a pore, the elongation, emerges.

From the large number of existing fractal dimensions (e.g. Burrough, 1989), two were selected which have already been successfully applied to staining patterns of macro-pores (Hatano et al., 1992). In contrast with the Euclidean geometry, where values are only expressed as integers, fractal dimensions apply to objects that are in shape somehow between a point and a line or between a line and a plane.

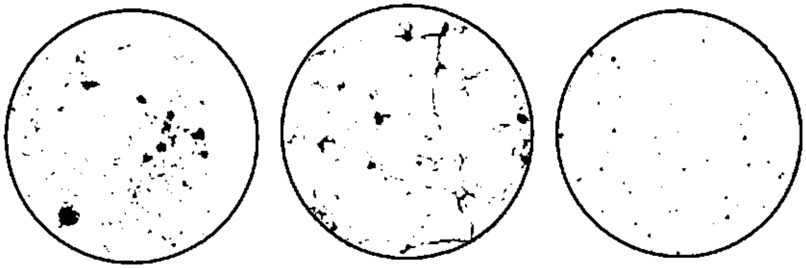
The shape fractal dimension, $D_s$, is related to the basic shape of an object (Hatano et al., 1992). $D_s$ values range from 0 to 2, with 0 indicating a point, 1 a line and 2 a plane. An estimate for $D_s$ is obtained by dividing the pattern into squares with size *r* and counting the number of squares *I* with one or more pores inside. By repeating this process for different sizes *r*, a double logarithmic regression can be obtained, resulting in the fractal dimension $D_s$ as the slope of this regression (Table 5.2). Hatano and Booltink (1992) obtained values of $D_s$ for a well-structured clay soil and found a statistically significant empirical equation between $D_s$, $A$, and bypass flow at laboratory scale. Including this fractal dimension for simulating water dynamics at field scale resulted in an accurate prediction of bypass flow in a heavily structured clay soil (Booltink, 1994).

The second fractal dimension, $D_{pe}$, is related to the average smoothness of the boundary line of pores in a pattern (Hatano et al., 1992). Values range from 1, indicating a smooth boundary, till 2, a very irregular pore boundary. $D_{pe}$ is obtained by performing a double logarithmic regression analysis on $A_i$ and $Pe_i$ of all the pores in a pattern. The slope of this regression line is the $D_{pe}$. Pachepsky et al. (1996) used this parameter successfully to describe effects of management on the micro-porosity of a silty loam soil.

### *Distribution parameters*

Spatial point patterns consist of a finite number of locations observed in a spatial region. Stein et al. (1997) used spatial distribution functions to evaluate the distribution of pores in staining patterns. In general, spatial distribution functions are used to test spatial patterns on their distribution which can be clustered, regular or completely random. Several distribution functions can be used to quantify and test patterns such as "inter-event distances", "nearest neighbour distances" and "point to nearest neighbour distances" (Diggle, 1983). Van Noordwijk et al. (1993) applied the "point to nearest neighbour distances" on root distribution maps and concluded that this function also expresses the average distance from a point in the soil to the nearest plant root. This technique was used here to express the distribution of distances from a random point in the soil to the nearest macro-pore, which is an important parameter considering interaction of water between macro-pores and soil matrix. From the distribution function three points are selected as indicators: percentage of the soil matrix within a distance of 5, 10 and 20 mm from a macro-pore, denoted as *Dist05*, *Dist10*, and *Dist20*.

A commonly applied geostatistical tool is the variogram. The variogram measures the dependence between observations as a function of the distance between their locations. For spatial point patterns, with a value 1 indicating a pore and 0 indicating the soil matrix, an indicator variogram can be calculated. The variogram was calculated by randomly selecting 10000 grid-points from each pattern. An exponential function was fitted through the calculated variogram values yielding the *Range*, *Sill* and *Nugget* of the point pattern. The *Range* is the distance up to which a spatial dependency exists. The *Sill* is the value of the variance of the observations at a greater distance than the *Range*, the uncorrelated observations. The *Nugget* is an indicator for the small scale variability.



**Bio-1-10** **Conv-1-30** **Perm-2-40**

**Figure 5.1. Example of three different staining patterns used for a detailed description. Bio-1-10 is biodynamic management, first replicate, depth 10 cm; Conv-1-30 is conventional management, first replicate, depth 30 cm; and Perm-2-40 is permanent grassland, second replicate, depth 40 cm.**

**Table 5.3. Parameter values for macro-porosity of the three patterns.**

| Parameter | | Bio-1-10 | Conv-1-30 | Perm2-40 |
|---|---|---|---|---|
| $N$ | (cm$^{-2}$) | 0.312 | 0.247 | 0.107 |
| $A$ | (cm$^{2}$ cm$^{-2}$) | 0.023 | 0.029 | 0.004 |
| $\overline{A}_{por}$ | (cm$^{2}$) | 0.072 | 0.119 | 0.039 |
| $Pe$ | (cm cm$^{-2}$) | 0.261 | 0.367 | 0.071 |
| $\overline{Pe}_{por}$ | (cm) | 0.836 | 1.483 | 0.665 |
| $CPe$ | (cm cm$^{-2}$) | 0.237 | 0.319 | 0.069 |
| $\overline{CPe}_{por}$ | (cm) | 0.758 | 1.288 | 0.639 |
| $S$ | (-) | 1.242 | 1.367 | 1.137 |
| $CS$ | (-) | 1.186 | 1.275 | 1.104 |
| $D_s$ | (-) | 1.227 | 1.149 | 0.814 |
| $D_{pe}$ | (-) | 1.161 | 1.286 | 1.040 |
| *Dist05* | (%) | 32 | 25 | 11 |
| *Dist10* | (%) | 62 | 50 | 28 |
| *Dist20* | (%) | 91 | 83 | 70 |
| *Range* | (cm) | 1.56 | 0.20 | 0.76 |
| *Nugget* | (-) | 0.005 | 0.000 | 0.002 |
| *Sill* | (-) | 0.031 | 0.021 | 0.003 |

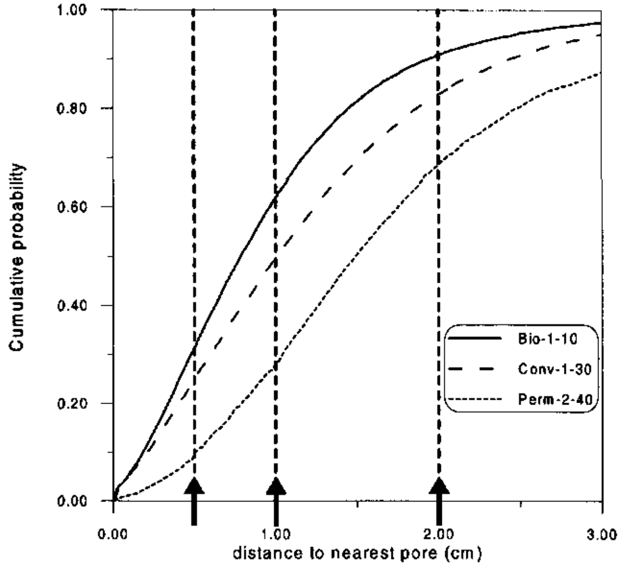


Figure 5.2. "Point to nearest neighbour distances" distributions for the three example patterns.

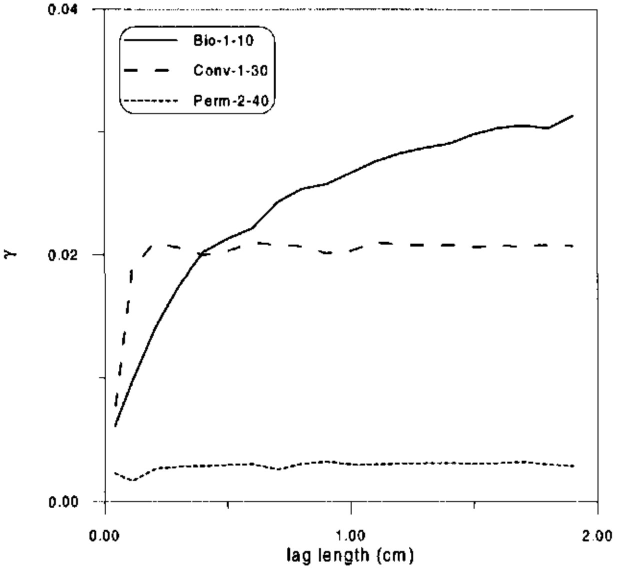


Figure 5.3. Indicator semi-variograms for the three patterns.

# RESULTS AND DISCUSSIONS

## *Examples*

Three different patterns (Fig. 5.1) are selected to illustrate the methodology and application of the different parameters for macro-porosity. The most important different features are: a mixture of large and small pores (*Bio*-1-10), presence of cracks (*Conv*-1-30), and small circular pores (*Perm*-2-40). The parameters for macro-porosity of these four examples are given in Table 5.3.

Basic macro-porosity parameters, ranging from *N* till *CS* (Table 5.2), clearly reflect the characteristics of the patterns. *Perm*-2-40 has a low amount of pores (*N*, *A*, *Pe*, *CPe*), pores are small ($\overline{A}_{por}$, $\overline{Pe}_{por}$, $\overline{CP}_{por}$), the boundary of the pores are smooth (*S*) and pores are circular (*CS*). *Bio*-1-10 has a higher *N*, and also the average pore size is greater. The somewhat higher *S* and *CS* parameters indicate more irregular pores. Finally, *Conv*-1-30 has the highest average pore size and the most irregular pores.

The fractal dimension $D_{pe}$, the smoothness of the boundary of the pores, shows, as expected, the same trend as the *CS*. The other fractal dimension, $D_s$, related to the basic shape of an object, is higher for *Bio*-1-10 than for *Conv*-1-30. This would indicate a more line structure for *Bio*-1-10 than for *Conv*-1-30, which contradicts the observations (Fig. 5.1).

**Table 5.4. Number of correlation coefficient > 0.9 and <0.25 for the 17 parameters.**

| Parameters | > 0.9 | <0.25 |
|---|---|---|
| $N$ | 1 | 6 |
| $A$ | 3 | 2 |
| $\overline{A}_{por}$ | 1 | 4 |
| $Pe$ | 4 | 2 |
| $\overline{Pe}_{por}$ | 2 | 3 |
| $CPe$ | 4 | 2 |
| $\overline{CPe}_{por}$ | 1 | 3 |
| $S$ | 1 | 2 |
| $CS$ | 1 | 3 |
| $D_s$ | 0 | 2 |
| $D_{pe}$ | 0 | 2 |
| *Dist05* | 3 | 2 |
| *Dist10* | 3 | 2 |
| *Dist20* | 0 | 8 |
| *Range* | 0 | 16 |
| *Nugget* | 0 | 11 |
| *Sill* | 2 | 2 |

The "point to nearest neighbour distances" distributions are shown in Fig. 5.2. It can be observed that, taking *Bio*-1-10 as an example, 32% of the soil is within a distance of 0.5 cm of a macro-pore, 62% is within 1.0 cm, and 91% of the soil is situated closer than 2.0 cm from the nearest macro-pore. For *Perm*-2-40 the average distances from a point in the soil matrix to the nearest macro-pore are highest. Distances for *Bio*-1-10 are lowest, indicating that interactions between soil matrix and macro-pores are highest.

Finally, the indicator variograms for the three examples are plotted in Fig. 5.3. Parameters of the fitted exponential model gives the largest *Range* for *Bio*-1-10, indicating that spatial dependency exists over a large length. The low *Sill* values for *Perm*-2-40 shows that the variance in observations is low.

**Table 5.5. Parameter pairs with a correlation coefficient > 0.9.**

| | | Corr. coef. |
|---|---|---|
| *Pe* | *CPe* | 0.98 |
| $\overline{Pe}_{por}$ | $\overline{CPe}_{por}$ | 0.97 |
| *S* | *CS* | 0.97 |
| *Dist05* | *CPe* | 0.97 |
| *Pe* | *A* | 0.96 |
| $\overline{Pe}_{por}$ | $\overline{A}_{por}$ | 0.96 |
| *Dist05* | *Pe* | 0.96 |
| *Dist05* | *Dist10* | 0.95 |
| *A* | *Sill* | 0.94 |
| *Pe* | *Sill* | 0.92 |
| *N* | *Dist10* | 0.91 |
| *CPe* | *Dist10* | 0.91 |
| *A* | *CPe* | 0.91 |

### *Correlation analysis*

The three examples presented were selected to clarify the methodology and application of the different parameters for macro-porosity. We return now to the complete population and concentrate first on the correlation between the different parameters. Table 5.4 summarizes the correlation matrix, presenting for each parameter the number of correlation coefficients with absolute values higher than 0.9 or lower than 0.25. Most parameters have one or more high correlations with other parameters and only a few correlation coefficients lower than 0.25. $N$, $D_s$, $D_{pe}$, *Dist20* and in particular *Nugget* and *Range*, have a strong capacity to describe unique macro-porosity properties that are not described by other parameters. Table 5.5 shows all parameter pairs with a correlation coefficient higher than 0.90. Remarkable is the strong correlation between *Pe* and *CPe* and, as a result of this, between *S* and *CS*. Therefore, no clear distinction exists between the small irregularity of pores, i.e. the roughness of the pore-boundary, and the large scale irregularity, i.e. the elongation. A similar conclusion was found by Ringrose-Voase and Bullock (1984). However, both *S* and *CS* are in principle attributes of single pores and are used here as an average value for the whole pattern. However, this still yielded a relatively high correlation coefficient of 0.91 considering all the individual pores.

### *Factor analysis*

Principal component analysis on the correlation matrix shows that five factors explained 95% of the variation. The first factor explained 62% followed by 18, 6, 5 and 5% for the other four factors, respectively. The five factors with their factor-loadings are given in Table 5.6.

**Table 5.6. Factor loadings of the principal component analysis using varimax rotation method. Values higher than 0.75 are indicated.**

| Parameter | *Factor1* | *Factor2* | *Factor3* | *Factor4* | *Factor5* |
|---|---|---|---|---|---|
| $N$ | **0.96** | -0.06 | 0.21 | 0.04 | -0.01 |
| $A$ | 0.70 | 0.62 | 0.20 | -0.06 | -0.03 |
| $\overline{A}_{por}$ | 0.25 | **0.91** | 0.23 | -0.05 | 0.04 |
| $Pe$ | **0.83** | 0.44 | 0.27 | -0.08 | -0.01 |
| $\overline{Pe}_{por}$ | 0.24 | **0.88** | 0.37 | -0.12 | 0.09 |
| $CPe$ | **0.87** | 0.36 | 0.28 | -0.08 | 0.03 |
| $\overline{CPe}_{por}$ | 0.14 | **0.84** | 0.42 | -0.14 | 0.15 |
| $S$ | 0.23 | 0.58 | **0.76** | -0.03 | 0.11 |
| $CS$ | 0.10 | 0.48 | **0.84** | -0.02 | 0.12 |
| $D_s$ | 0.71 | 0.53 | 0.36 | 0.06 | 0.12 |
| $D_{pe}$ | 0.27 | 0.26 | **0.86** | -0.21 | 0.10 |
| *Dist05* | **0.91** | 0.32 | 0.22 | -0.05 | -0.02 |
| *Dist10* | **0.96** | 0.18 | 0.10 | 0.00 | 0.05 |
| *Dist20* | **0.88** | 0.06 | -0.19 | 0.11 | 0.11 |
| *Range* | 0.04 | -0.15 | -0.13 | **0.97** | -0.09 |
| *Nugget* | 0.04 | 0.11 | 0.16 | -0.09 | **0.97** |
| *Sill* | 0.66 | 0.66 | 0.20 | -0.13 | -0.06 |

*Factor1* can be considered as the "total quantity" factor. It contains all the parameters that are influenced by the amount of macro-pores: *N, Pe, CPe.* Also the three parameters from the "point to nearest neighbour distances" distribution: *Dist05, Dist10, Dist20* are related to this "total quantity" factor. The factor-loading for *A* was not very high for *Factor1*, although it is clearly related to the "total quantity". Reason for this is the communality of *A* for *Factor1* as well as for *Factor2*.

*Factor2* can be regarded as the "individual pore quantity" and is mainly determined by $\overline{A}_{por}$, $\overline{Pe}_{por}$ and $\overline{CPe}_{por}$. *Factor3* accounts for the shapes of the pores, including the two shape parameters related to the individual pores, *S* and *CS*, and also the overall boundary shape fractal dimension $D_{pe}$. Finally, *Factor4* and *Factor5* are determined by the *Range* and *Nugget* parameters. These factors are of less importance as they explain only 5% of the variation.

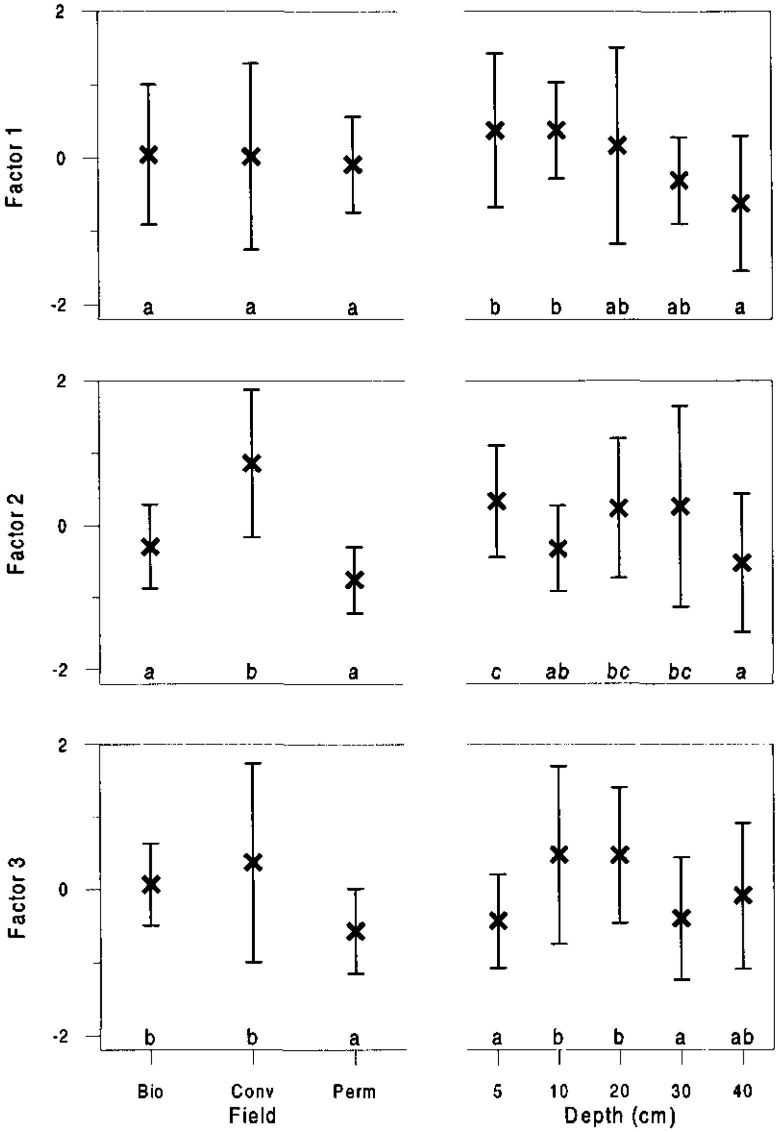


**Figure 5.4. Average factor scores with their associated standard deviations, expressed per field and per depth. Letters indicate whether differences between fields or between depths are significant (P = 0.05).**

### *Field and depth differences*

The five factors are used to indicate differences between fields and depths, concentrating on the first three factors. Fig. 5.4 shows average factor scores with their standard deviations. *Factor1*, the "total quantity", was not significantly different for the three fields, but standard deviations indicate a high variability for *Conv* and a low variability for *Perm*. On the other hand, a clear depth effect could be noticed, with lower values with increasing depths. The standard deviation at 20 cm was high, indicating a distinctive soil layer with at some spots a low amount and at other spots a high amount of macro-pores, which can be explained by the occurrence of plough layers. Only for some patterns, macro-pores are continuous till 40 cm, which explains the relatively high variation at depth 40 cm.

The "individual pore quantity", *Factor2*, was highest for *Conv* indicating that the individual pores are larger in comparison with *Bio* and *Perm*. Also standard deviation was highest for *Conv*, caused by the occurrence of cracks as well as vughs and channels. Low factor score and low standard deviation at 40 cm, shows that the continuous macro-pores are small and homogeneous in size.

*Factor3*, the "shape", has a very distinctive field and depth effect. *Perm* has a low value representing circular pores. This correspond with the dominant pore types in *Perm*: the biopores formed by worms. *Bio* and *Conv* are not significantly different for this "shape" factor. In contradiction with low standard deviation at 40 cm for *Factor2*, *Factor3* has a high standard deviation at this depth. This leads to the conclusion that the continuous macro-pores are small and similar in size, but with a large variation in shape.

## CONCLUSIONS

Selection of the most appropriate parameters to describe macro-porosity, based on the presented results, depends upon the objective of the study. Analysing staining patterns in an explanatory way, requires parameters related to the three distinguished factors: "total quantity", "individual pore quantity" and "shape". $N$ is the most appropriate parameter to describe "total quantity", considering the factor loadings. Although *Dist10* has a similar factor loading, $N$ is a much more straightforward parameter, and is therefore preferred. $\overline{A}_{por}$ is the best parameter to describe "individual pore quantity". It has the highest factor loading and is also relatively easily obtainable. Considering the factor loadings for *Factor3*, $D_{pe}$ is the most appropriate parameter to describe "shape". However, including also complexity of the parameter as criterion, a logical selection to quantify "shape" will be $S$. Characterising macro-porosity in a more empirical way, requires parameters not related to one factor, but an expression for the overall properties. Three parameters, $A$, $D_s$ and *Sill*, are not related to any of the five distinguished factors, assuming 0.75 as the distinctive factor-loading value. Consideration of the correlation analysis, leads to the conclusion that $D_s$ will be the most appropriate parameter. Hatano and Booltink (1992) used this parameter, combined with $A$, successfully to predict the amount of bypass in a clay soil.

The three different management types have not led to significantly different quantities of macro-pores in the three fields. However, individual pore sizes and shapes of pores are clearly influenced by management. Increasing depths show reducing "total quantity" values. Therefore, bypass flow will be limited only to the topsoil. This was in agreement with results obtained by Droogers and Bouma (1996). They used a simulation model without bypass flow for the same fields as used in this study, and reported that differences in measured and simulated moisture contents were restricted to the topsoil.

## ACKNOWLEDGEMENTS

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# Chapter 6

# WATER ACCESSIBILITY TO PLANT ROOTS IN DIFFERENT SOIL STRUCTURES OCCURRING IN THE SAME SOIL TYPE

**Abstract** The capacity of a soil to supply roots with water and nutrients for crop growth is important when defining sustainable land management which implies maintenance of production and reduction of production risks. Not only the amount of "available" water is important but also its "accessibility", which differs among different soil structures. Different structures within one soil series were associated with three types of management: (i) conventional, temporary grassland (*Conv*), (ii) biodynamic, temporary grassland (*Bio*) and (iii) conventional permanent grassland (*Perm*). Transpiration of barley plants, under identical circumstances, and the associated rooting patterns, were measured in five large undisturbed cores from each of the three soil structures. Management had significantly changed bulk density, organic matter content and porosity. Measured transpiration showed significant differences with highest amounts for *Perm* followed by *Conv* and lowest amounts for *Bio*. "Rooting pattern characteristics", defined as the relation between a series of hypothetical extraction zones around each root and the volumes of excluded soil were determined for the three structures. These "rooting pattern characteristics" were most favourable for *Perm*, followed by *Bio* and *Conv*, respectively. The "water supply characteristics", defined as the number of days the soil can satisfy a transpiration demand of 5 mm $d^{-1}$ as a function of a hypothetical extraction zone, reflects the capacity of the soil to supply roots with water. These "water supply characteristics" combined with the "rooting pattern characteristics" were used to quantify the accessibility of soil water. Accessibility was highest for *Perm* and *Conv* with 95% and 94% respectively, followed by *Bio* with 68%. When used in a simulation model and compared with simulations implicitly assuming total accessibility, measured transpirations were better simulated by introducing the expression for water accessibility.

## INTRODUCTION

Soils which are identical from a genetic and taxonomic point of view, can form considerably different soil structure types as a result of applied management (Kooistra et al., 1985). It is evident that *strategic* and *tactical* management decisions play an important role in this soil structure development, but *operational* management decisions often play the most important role. For example, Droogers et al. (1996) compared a biodynamic and a conventional management system (distinguished at the strategic level) and concluded that the biodynamic system was favourable in terms of potential productivity at the strategic level, but that the degradation risk (to be considered at the operational level) was higher.

Soil structure has an important impact on soil quality and sustainability. A comparative study between different management types and soil structures within one soil type, can therefore be used to deduce sustainable management systems. The FAO (1993) defined four criteria for sustainable land management: (i) maintain or enhance production and services; (ii) reduce the level of production risk; (iii) protect the potential of natural resources and prevent degradation of soil and water quality, and (iv) be economically viable and socially acceptable. Key aspect of production and especially production risk, is the capacity of a soil to supply roots with adequate water and nutrients for crop growth.

The amount of water and dissolved solutes which is "available" for root water uptake is often defined as the amount of soil water between field capacity and wilting point. A soil matric pressure of -10 or -33 kPa for field capacity and -1500 kPa for wilting point are commonly used values (FAO, 1979). However, this wilting point is more determined by the soil than by the plant (Hulugalle and Willatt, 1983), as suction in plants can go up to 4 MPa (Grace, 1993). In addition, it is also not likely that all soil water that is "available" is "accessible" for roots, especially in coarsely aggregated soils. So far, no operational procedures have been defined to characterize "accessibility" of water. Bouma (1990) makes a distinction between "available" and "accessible" water for root uptake and introduced a methodology to take this accessibility into account during modelling activities. Bouma and Van Lanen (1989) presented an exploratory case study which clearly shows that accessibility can have a strong impact on crop growth and water dynamics of a soil. However, experimental data have so far not been presented.

Accessibility of soil water depends on the one hand on root density and root distribution, and on the other hand on the ability of the soil to supply roots with water at a certain rate. Rooting patterns are mainly influenced by the penetration resistance and thus by the density and aggregation of the soil and can directly be observed. Availability is mainly a function of the soil hydraulic characteristics. Laboratory studies demonstrate that soil compaction limits root penetration and the ability of the plant to take up water (e.g. Materechera et al., 1993). Also, the effects of aggregate size and strength have been studied and show clearly that aggregates can impede root growth affecting the water and nutrient uptake ability of plants (e.g. Logsdon et al., 1987; Misra et al., 1986). Many field studies have been performed to relate experimentally induced soil degradation, such as extreme compaction by machinery, to root density and root distribution (e.g. Tardieu, 1988). More relevant would be a quantification of the effects of different types of structure, formed by different types of normal management practices, on root water uptake.

In this study three soil structure types resulting from different management practices in one type of soil, were compared in terms of their capacity to allow crop transpiration. Seedlings were planted in undisturbed large soil samples, and transpiration was monitored under identical conditions. Rooting patterns were observed and quantified, providing information on density and distribution of roots. Additionally, the capacity of the soil in each of the three structures to supply roots with water was quantified using the soil hydraulic characteristics. The "rooting pattern characteristics" combined with the "water supply characteristics" were used to obtain a quantitative description of the "accessibility" of soil water.

Finally, an integrated dynamic simulation model for water movement in the unsaturated zone and crop growth was used to simulate measured transpiration in two ways. First, by assuming total accessibility of the soil water; secondly, by applying the obtained accessibility from the "rooting pattern characteristics" and the "water supply characteristics".

In summary, the objective of this study was to characterize the impact of accessibility of soil water on crop behaviour by: (i) comparing transpiration of crops growing in the same soil type under identical physical boundary conditions, but with different soil structures, and (ii) explaining differences obtained by considering rooting patterns and soil hydraulic characteristics.

## MATERIALS AND METHODS

Three sites were selected each under a different management system, but all within the same soil type, a loamy mixed mesic Typic Fluvaquent (Soil Survey Staff, 1975), in the south-western part of the Netherlands. First site, abbreviated as *Bio*, has been managed for 70 years according to biodynamic principles (Reganold, 1995), which implies that no chemical fertilizer or chemical crop protection was utilized, but that soil quality was maintained by a favourable crop rotation and by use of organic fertilizer. However, soil tillage did not deviate from conventional systems and consisted of ploughing to a 30 cm depth. The second site, denoted as *Conv*, belonged to an experimental farm with a conventional management system for the region, including a crop rotation of potatoes, grassland, sugarbeet and grains and use of agrochemicals. On both sites a field with temporary grassland, applied as part of crop rotation, were used for this study. The *Bio* field was used as temporary grassland for two years, the *Conv* field for three years. Finally, a site was selected which had been permanently under grassland since 1947 (*Perm*). All management systems have been applied for decades, which guarantees a soil condition in an equilibrium state (Phillips and Phillips, 1984). Detailed descriptions of management practices and soil characteristics were presented by Droogers et al. (1996).

Five undisturbed soil cores with a height and diameter of 20 cm were collected from each structure type at depths from 10 cm to 30 cm. In addition, eight small 300 cm$^3$ samples were taken to determine the water retention and conductivity curve, by multi-step outflow method (Van Dam et al., 1994) and crust-method (Booltink et al., 1991).

The 15 undisturbed samples (five per structure type) for the transpiration experiment were saturated and some additional nutrients were added to ensure growth without nutrient limitations. Then, samples were placed on a sand-box with a matric pressure of -5 kPa to obtain identical soil matric pressures for all samples. In every sample seven barley seedlings were planted and the top and bottom of the samples were covered with plastic to prevent soil evaporation. For every plant a small incision was made in the plastic to allow uninhibited growth. Seven barley plants per sample corresponds with a plant density of 220 plants m$^{-2}$, which is commonly used in field situations. Samples were placed in a greenhouse and were weighed at 2 day intervals, thus providing information on transpiration. No additional water was added.

After the plants failed to take up any more water due to drought stress, three randomly selected samples from each structure type were sliced horizontally at 10 cm and 15 cm depth. Rooting patterns were recorded in the middle of these sections using a 24 x 24 grid with gridsizes of 0.5 cm. This grid covers an area 12 x 12 cm and did not cover the entire soil core, which prevents possible observation errors by edge effects. For each grid-cell an observation was made whether a root was present or not. The observed rooting patterns were quantified by determining the relation between a series of hypothetical extraction zones and the remaining "dead volume" (De Willigen and Van Noordwijk, 1987). The hypothetical extraction zone was defined as a circle around each root and the "dead volume" as the soil fraction which was not located within the extraction zone of any root. This characteristic relation between the hypothetical extraction zone and the dead volume will be denoted as "rooting pattern characteristic", and is a function of the number of roots and their distribution. Van Noordwijk et al. (1993) showed that this method leads to a frequency distribution of "nearest neighbour distances" (Diggle, 1983).

Besides the "rooting pattern characteristic", the ability of the soil to transport water inside unrooted aggregates to the edges of the aggregates should also be considered. It is clear that increasing aggregate sizes will reduce transpiration as more water will have to flow from inside the unrooted aggregates to the outside. To quantify this dynamic behaviour of soil water in aggregates, the one-dimensional Richards-Darcy equation without gravity term was used:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\frac{\partial h}{\partial x}\right] \tag{6.1}$$

where $\theta$ is the volumetric water content ($m^3\ m^{-3}$), $x$ is horizontal coordinate (m), $t$ is time (d), $K$ is hydraulic conductivity ($m\ d^{-1}$), and $h$ is soil water pressure head (m).

A modified version of the Hyswasor model was used to solve this equation with an implicit finite element method (Dirksen et al., 1993). Input requirements were the water retention curve and the hydraulic conductivity curve for each structure type. Initial matric pressure was set at -6 kPa, which corresponds to the average moisture conditions in the large samples of the transpiration experiment. This -6 kPa corresponds, according to the equivalent pore size distribution theory (e.g. Bouma, 1991), to a pore diameter of 46 μm, permitting the use of the bulk soil hydraulic properties as the aggregate hydraulic properties. For varying sizes of extraction zones, which can be considered as half the size of an aggregate, and transpiration demands, water flow from inside aggregates to the outside can be calculated assuming one dimensional horizontal flow. Here, a somewhat arbitrary transpiration demand of 5 mm $d^{-1}$ was taken as an input value, which is about the maximum transpiration rate in the Netherlands (De Willigen and Van Noordwijk, 1987). Maximum root suction was set at 4 MPa, which is the maximum value a plant can reach (Grace, 1993). Output was the relation between the size of the extraction zone and the number of days the soil can supply this transpiration demand of 5 mm $d^{-1}$. This relation between size of the extraction zone and number of days will be denoted as the "water supply characteristic".

The "rooting pattern characteristic" combined with the "water supply characteristic" were used to determine the fraction accessible water in the three soil structures. First, the number of successive days is selected with a critical transpiration demand of 5 mm $d^{-1}$. Analysis of daily values of potential transpiration in The Netherlands for a period of 35 years showed that a period of 6 or more successive days with potential transpiration $\geq 5$ mm $d^{-1}$ occurs in 5% of the years (KNMI, 1959-1993). The "water supply characteristics" were used to transform these 6 days to critical extraction zones. These critical extraction zones for each structure type were converted to accessible soil fractions by use of the "rooting pattern characteristics".

The WAVE model (Vanclooster et al., 1994) was used to simulate the transpiration experiment in two ways. First, simulations were performed assuming total accessibility of soil water. Secondly, the simulations were carried out considering the accessibility $v/v_0$:

$$\theta_{acc} = \theta_{avail} * v / v_0 \qquad (6.2)$$

where $\theta_{acc}$ is the amount of accessible soil water ($m^3\ m^{-3}$), $\theta_{avail}$ is the amount of available soil water ($m^3\ m^{-3}$), and $v/v_0$ the accessibility fraction (-) with $v$ is accessible soil volume ($m^3$) and $v_0$ is total soil volume ($m^3$) (e.g. Bouma and Van Lanen, 1989; Bouma, 1990).

# RESULTS

## *Soils*

The morphology of the soils reflects the effects of the different management types in a qualitative way. The *Bio* field had moderately large peds in the root zone and somewhat stronger large peds below the root zone. The morphology of *Conv* was quite comparable with *Bio*, but here the peds were stronger and more dense. The similarity in morphology between these two fields, could be explained by comparable tillage practices. On the other hand, *Perm* had a loose crumb structure with many biologically induced pores.

**Table 6.1. Basic soil properties for the three distinguished soil structure types for the top soil. *Bio* is biodynamic temporary grassland, *Conv* is conventional temporary grassland and *Perm* is permanent grassland.**

| | Bulk density | | Organic matter | | Porosity | |
|---|---|---|---|---|---|---|
| | avg. | std. | avg. | std. | avg. | std. |
| | — $Mg\ m^{-3}$ — | | —— % —— | | — $m^3\ m^{-3}$ — | |
| Bio | 1.47 b | 0.065 | 3.3 b | 0.59 | 0.42 b | 0.015 |
| Conv | 1.68 c | 0.061 | 1.7 a | 0.05 | 0.36 a | 0.021 |
| Perm | 1.38 a | 0.109 | 5.0 c | 0.57 | 0.46 c | 0.023 |

*Different letters indicate a statistically significant difference (LSD, $P \leq 0.05$)*

Basic soil properties were all significantly different for the three fields (Table 6.1). Soil hydraulic characteristics, average water retention and conductivity curves, for the three structure types are presented in Fig. 6.1.

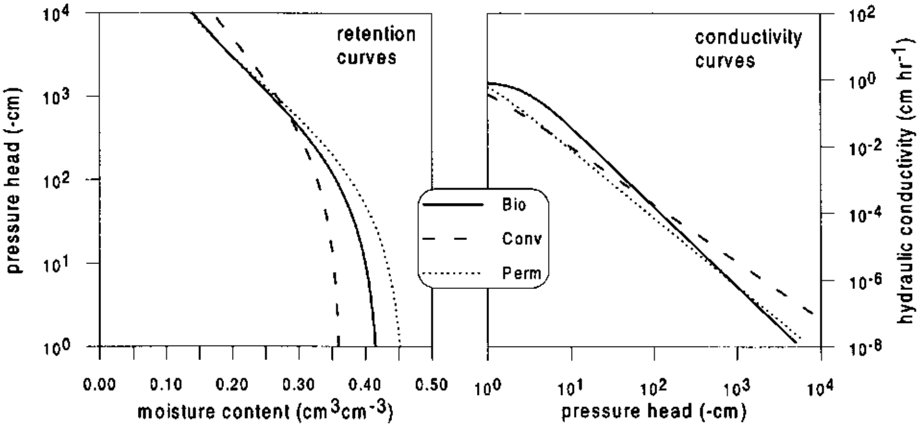

**Figure 6.1. Soil hydraulic characteristics for the three soil structure types. *Bio* is biodynamic temporary grassland, *Conv* is conventional grassland and *Perm* denotes the permanent grassland.**

**Table 6.2. Total measured transpiration and initial moisture content for the three structure types. Values in mm were divided by the sample height of 20 cm to obtain results as volumetric fractions in $m^3$ $m^{-3}$.**

| | Initial moisture content | | | Measured transpiration | | |
|---|---|---|---|---|---|---|
| | avg. | std. | avg. | avg. | std. | avg. |
| | mm | mm | $m^3$ $m^{-3}$ | mm | mm | $m^3$ $m^{-3}$ |
| Bio | 68.5 a | 0.7 | 0.342 | 42.1 a | 0.7 | 0.210 |
| Conv | 67.9 a | 1.6 | 0.340 | 44.4 b | 1.4 | 0.225 |
| Perm | 71.4 b | 2.7 | 0.357 | 50.1 c | 1.4 | 0.251 |

*Different letters indicate a statistically significant difference (LSD, $P \leq 0.05$)*

## *Transpiration*

The total amount of measured transpiration was significantly different for the three structure types and was highest for *Perm* followed by respectively *Conv* and *Bio* (Table 6.2). Variation within the five replicates was remarkable low, as indicated by the standard deviations. Transpiration as a function of time is shown in Fig. 6.2. Initial moisture contents at the start of the experiment were somewhat different for the three structure types, although samples were brought to the same matric pressure of -5 kPa. This can be explained by the different soil water retention characteristics of the soils (Fig. 6.1).

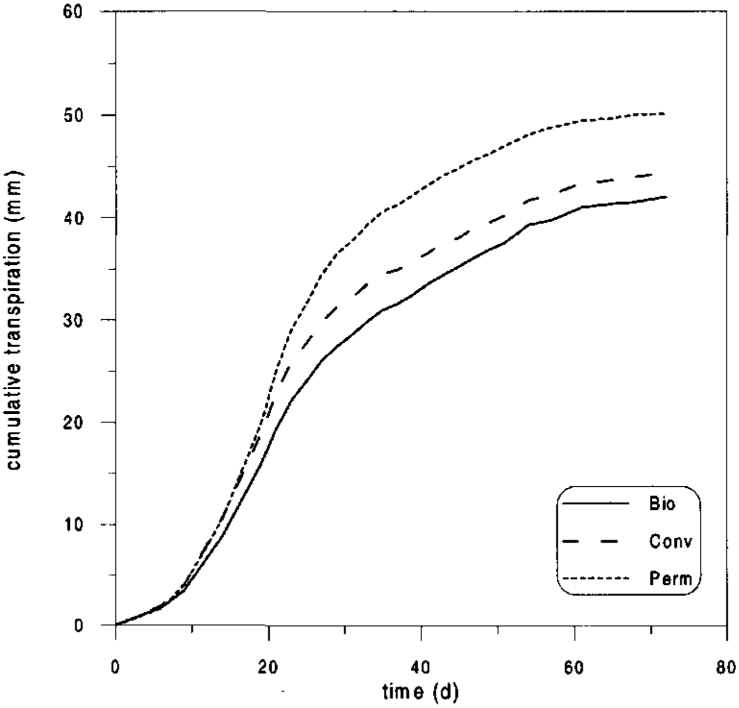

**Figure 6.2. Measured cumulative transpiration for the three distinguished soil structure types. Each curve represents the mean of five individuals.**

### *Rooting pattern characteristics*

To illustrate results obtained for "rooting pattern characteristics" two different examples are selected from 18 observed rooting patterns, and the results obtained are described in detail. First, the observed rooting patterns from the grid of 12 x 12 cm with gridsizes of 0.5 cm are shown in Fig. 6.3. *Bio*6-10 could be regarded as an example of a heterogeneously distributed rooting pattern, while roots in *Perm*6-10 were more homogeneously distributed. Secondly, the distance from each grid cell to the nearest root was measured, providing plots like Fig. 6.3. Clearly, *Bio*6-10 had more regions which were at greater distances from roots than *Perm*6-10. These results were combined into a distribution function of distances to the nearest root, the "rooting pattern characteristic", shown in Fig. 6.4 for the two cases. From this figure it can be seen, for example, that 50% of the soil volume was located more than 1 cm from the nearest root for *Bio*6-10, while this was only 20% for *Perm*6-10.

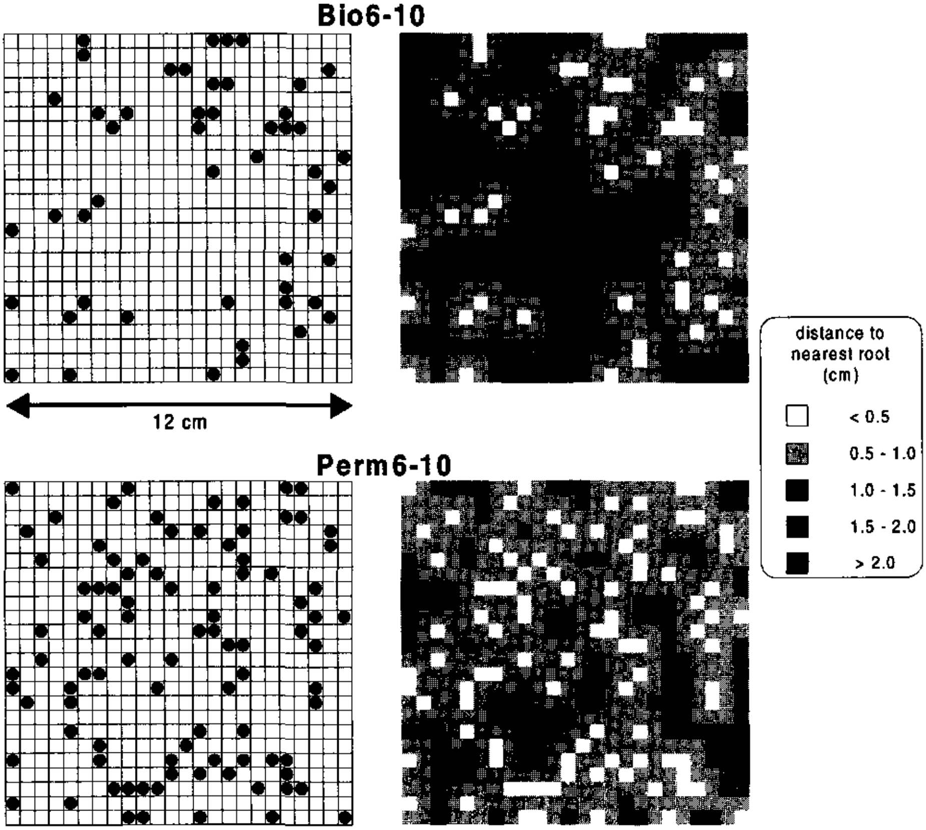

**Figure 6.3. Rooting patterns of two different cross sections from a *Bio* and a *Perm* section at 10 cm depth. For each grid-cell of 0.5 x 0.5 cm a dot indicates the presence of a root (left part). Measured distances to the nearest root for each grid-cell based (right part).**

**Table 6.3. Number of roots and root density observed on 6 horizontal sections of 12 x 12 cm per structure type.**

| | Number of roots avg. | std. | Root density $m^{-2}$ |
|---|---|---|---|
| Bio | 74 a | 15.3 | 5139 |
| Conv | 76 a | 14.8 | 5278 |
| Perm | 90 b | 9.9 | 6250 |

*Different letters indicate a statistically significant difference (LSD, $P \leq 0.1$)*

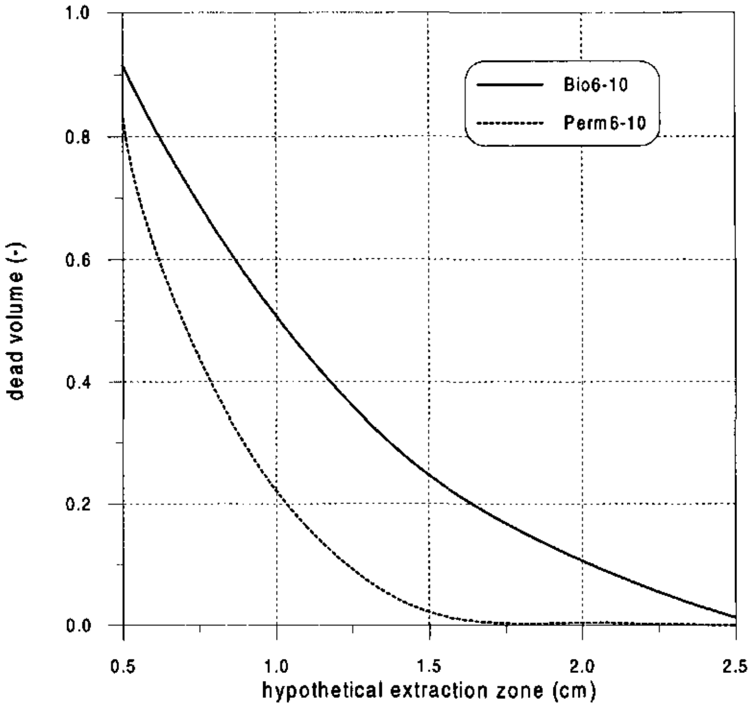

**Figure 6.4. Rooting pattern characteristic, which is the relation between the size of a hypothetical extraction zone around each root and the "dead volume" which is the soil fraction that does not fall into this extraction zone. Distribution is obtained from Figure 6.3.**

The two samples presented were not necessarily representative, but were selected to clarify the applied method. We return now to the complete population. A somewhat higher root density was observed for most samples at the interface between the soil and the container, especially for *Bio* and *Conv*. However, these roots were not included as the sampling grid covered only the centre of the core. Results from all the samples showed that the number of roots for *Perm* was highest, followed by *Bio* and *Conv* (Table 6.3). Differences were not significant at a 5% level but at 10% level, *Perm* differing from *Bio* and *Conv*. The "rooting pattern characteristics" showed that dead volumes were lower for *Perm* in comparison with *Bio* and *Conv* (Fig. 6.5). Although this relation is influenced by the total number of roots, it gives also an indication about the spatial distribution of the roots. For example, *Bio* and *Conv* had almost the same number of roots, but dead volumes were lower for *Bio*. In addition, the lower dead volumes for *Perm* were not only a result of the higher number of roots, but also of a more homogeneous rooting pattern.

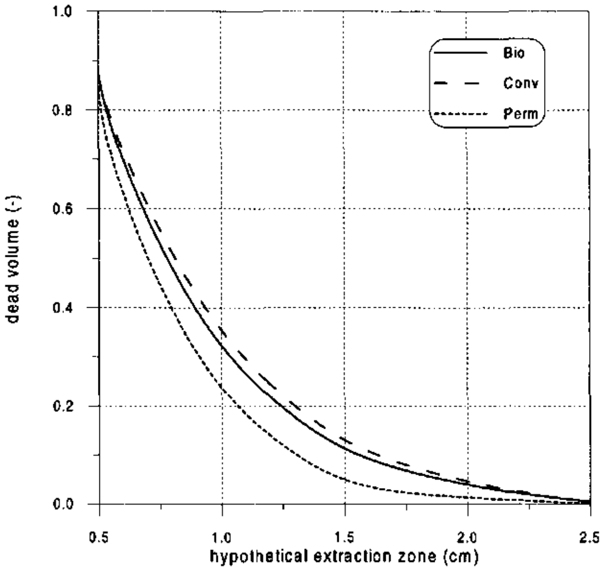

**Figure 6.5. Rooting pattern characteristic for the three distinguished soil structure types. Each curve represents the mean of six rooting patterns.**

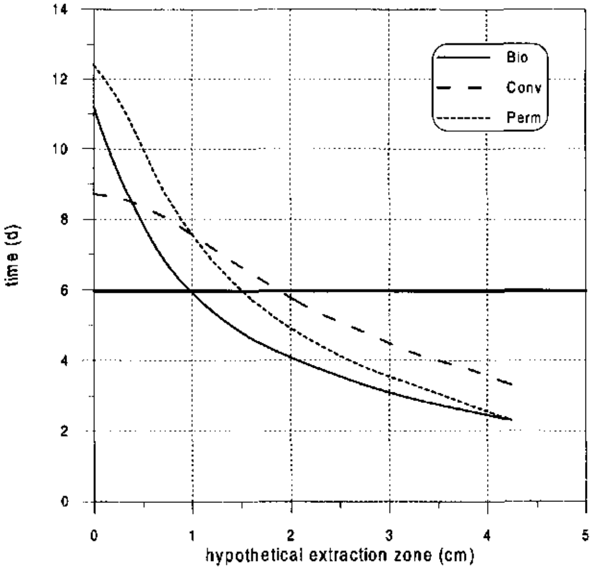

**Figure 6.6. Water supply characteristic, which is defined as number of days the soil can satisfy the transpiration demand of 5 mm $d^{-1}$ as a function of a hypothetical extraction zone.**

### *Water supply characteristics*

The "water supply characteristics" for the three structure types, calculated with the Richards-Darcy equation, are shown in Fig. 6.6. Extraction zones less than 1 cm gave the highest number of days the flux of 5 mm $d^{-1}$ could be sustained, with the highest for *Perm* followed by *Bio* and *Conv*. As expected, increasing extraction zones decreases the number of days that the given flux can be maintained. However, this process was more pronounced for *Bio* and *Perm* than for *Conv*, resulting in a higher accessibility for *Conv* in comparison with *Bio* and *Perm* for extraction zones larger than 1 cm.

**Table 6.4. Critical extraction zones and accessibilities as obtained from the "water supply characteristics" (Fig. 6.6) and the "rooting pattern characteristics" (Fig. 6.5).**

| | Critical extraction zone | Dead volume | Accessibility |
|---|---|---|---|
| | cm | - | - |
| Bio | 1.0 | 0.32 | 0.68 |
| Conv | 1.9 | 0.06 | 0.94 |
| Perm | 1.5 | 0.05 | 0.95 |

### *Accessibility*

The "water supply characteristics" were used to determine the critical extraction zone for the critical number of 6 days as defined before. Critical extraction zones were highest for *Conv* (1.9 cm) and lowest for *Bio* (1.0 cm), with *Perm* intermediate at 1.5 cm (Table 6.4). These critical extraction zones, which are only a function of the soil hydraulic properties, were used to determine the accessible soil volume by use of the "rooting pattern characteristics" (Fig 5). Accessibility was only 68% for *Bio* and 95% and 94% for *Perm* and *Conv* respectively.

## DISCUSSION AND CONCLUSIONS

### *Transpiration*

The applied management on *Perm* had resulted in a loose crumby soil structure, with a relatively high organic matter content, a high porosity and a low bulk density. The measured transpiration was highest. On the other hand, *Conv* had the lowest organic matter content, lowest porosity and highest bulk density, but measured transpiration was higher than for *Bio*, which had intermediate values for organic matter content, porosity and bulk density. Clearly, differences among basic soil characteristics cannot explain differences in measured transpiration. Rooting patterns have to be considered as well.

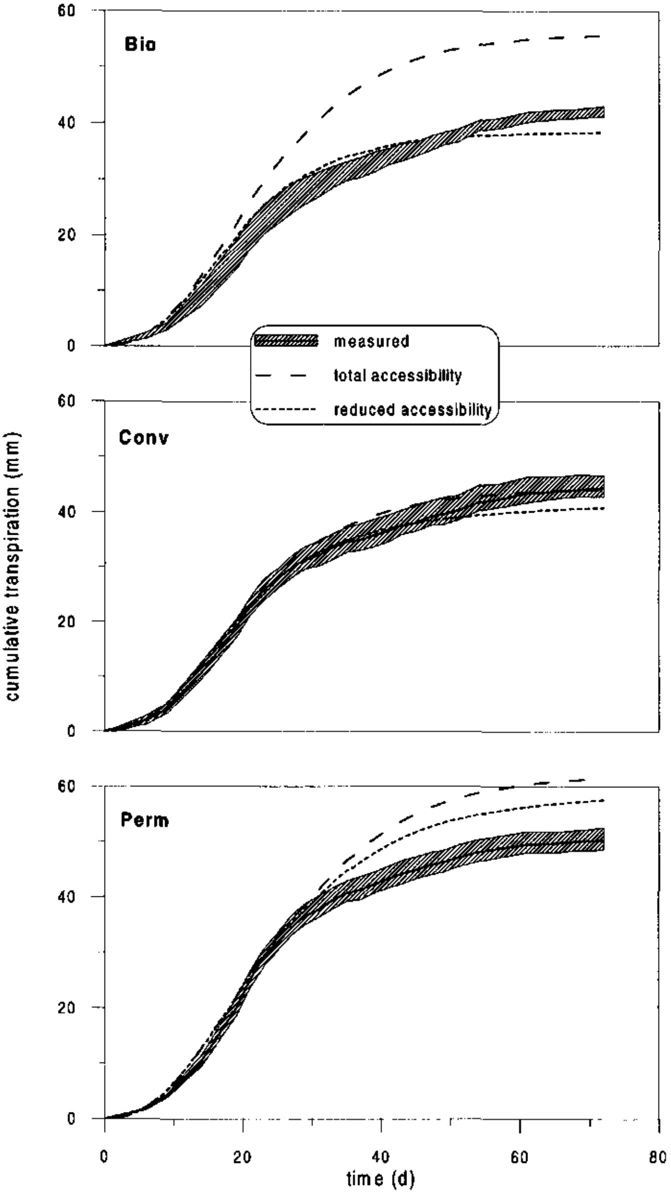

**Figure 6.7. Measured transpiration and simulated transpiration with total and reduced accessibility of soil water.**

### Accessibility

When explaining differences in transpiration among treatments two factors have to be distinguished: the number and distribution of roots and the ability of the soil to supply water to these roots. The first factor, the "rooting pattern characteristic", was favourable for *Perm*, which had a fine and loose soil structure, resulting in a high number of roots and a homogeneous distribution. The *Bio* and *Conv* field had fewer roots and a more clustered distribution pattern than *Perm*, although distribution for *Bio* was slightly more homogeneous than for *Conv*. The second factor, the ability of the soil to supply roots with water, the "water supply characteristic", was obviously better for *Conv* than for *Bio* and even for *Perm*. Differences can be explained by comparing hydraulic conductivity curves (Fig. 6.1). In the wet range conductivity was lowest for *Conv*, but in the dry range conductivity was highest, resulting in the highest fluxes when conditions were relatively dry. Combination of the two factors showed that accessibility was almost equal for *Perm* and *Conv*, but significantly lower for *Bio*. For *Perm*, favourable rooting properties resulted in this higher accessibility, while the ability of the soil to supply roots with water was the determining factor for *Conv*.

### Simulations

Simulated transpirations assuming complete accessibility were higher than measured transpirations. Introduction of the independently measured accessibility factor improved simulation results, especially for *Bio* (Fig. 6.7). For *Conv* the first 50 days of the experiment were better simulated when using the accessibility term. At the end of the experiment, however, measured transpiration was higher than the simulated. The explanation could be the use of one fixed value for accessibility, based on the critical transpiration demand of 5 mm $d^{-1}$, while over a longer period all soil water will become available. An other explanation for the lower simulated transpiration than the measured could be the characterization of the rooting patterns. A somewhat higher root density was observed near the edges of the cores, especially for *Bio* and *Conv*. These were not included in the "rooting pattern characteristics" and may account for the higher measured transpiration. Simulation results for *Perm* improved by incorporating the accessibility, although simulated transpiration was still higher than measured. Probably the less massive and more finely aggregated structure required a smaller extraction zone than was calculated.

Accessibilities obtained in this study can not be applied directly for other situations, because, aside from soil structure, they are also a well defined function of the boundary conditions of the assumed flow system. For example, root growth in this study took place in initially rather wet soils which do not severely hamper root growth into compacted aggregates. Also, transpiration was more constant during the experiment than would be the case under real field situations. However, the proposed procedure can be easily applied in other situations by assuming appropriate initial and boundary conditions. The procedure allows an independent expression of the effects of different rooting patterns on the accessibility of soil water.

# ACKNOWLEDGEMENTS

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# PART III

# Implications for soil survey

Chapter 7

Droogers, P., and J. Bouma. 1997. **Soil survey input in exploratory modeling of sustainable soil management practices.** Soil Sci. Soc. Am. J. (in press).

Chapter 8

Droogers, P., E. Meyles, and J. Bouma. **Soil quality of a Dutch soil series as influenced by long-term farm management practices.**

# Chapter 7

# SOIL SURVEY INPUT IN EXPLORATORY MODELING OF SUSTAINABLE SOIL MANAGEMENT PRACTICES

**Abstract** Soil survey information combined with exploratory simulation modeling was used to define indicators for sustainable land management. In one soil series in the Netherlands (the "geno-form"), three different "pheno-forms" were formed as result of different management practices. Locations were identified using a soil map and interviews with farmers. Organic matter, bulk densities and porosities were significantly different for the three "pheno-forms": biodynamic management (*Bio*); conventional management (*Conv*) and permanent grassland (*Perm*). By applying a dynamic simulation model for water movement, crop growth and N dynamics, the three "pheno-forms" were analyzed in terms of sustainability indicators by defining four scenarios based on productivity and N-leaching to the groundwater: (i) potential production, (ii) water-limited production, (iii) current management, and (iv) the environmental scenario. The latter was divided in EnvA: never exceeding the N-leaching threshold of 11.3 mg $l^{-1}$, EnvB: exceedance occurring in 1 out of 30 years, and EnvC: same in 3 out of 30 years. *Bio* obtained the lowest yield under current management, while yields for *Perm* were highest. EnvA could not be reached for *Perm* as a result of high mineralization rates. Obtainable yields for scenarios EnvA, EnvB and EnvC differed substantially, illustrating the importance of selecting "acceptable" risks in environmental regulation. The presented methodology demonstrates the important input of pedology in sustainability studies.

## INTRODUCTION

Sustainable land management practices are urgently needed all over the world to preserve the production potential of agricultural land while safeguarding environmental quality (e.g. FAO, 1993; UNCED, 1992). Following FAO (1993): "Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: (i) maintain and enhance production and services; (ii) reduce the level of production risk; (iii) protect the potential of natural resources and prevent degradation of soil and water quality; (iv) be economically viable and socially acceptable". Quantifying these four indicators is a useful method to evaluate the sustainability of a management system in a comprehensive manner.

Soils, as parts of complex ecosystems, play a crucial role in defining sustainable management practices. Even though semi-detailed soil surveys are available now in most developed countries and data have been stored in Geographic Iinformation Systems, few examples exist where such data are systematically being used in sustainability analyses. To the contrary, soil survey interpretation and land evaluation are still focused on defining suitabilities or limitations for given types of land use, which provide valuable information but with a rather different focus.

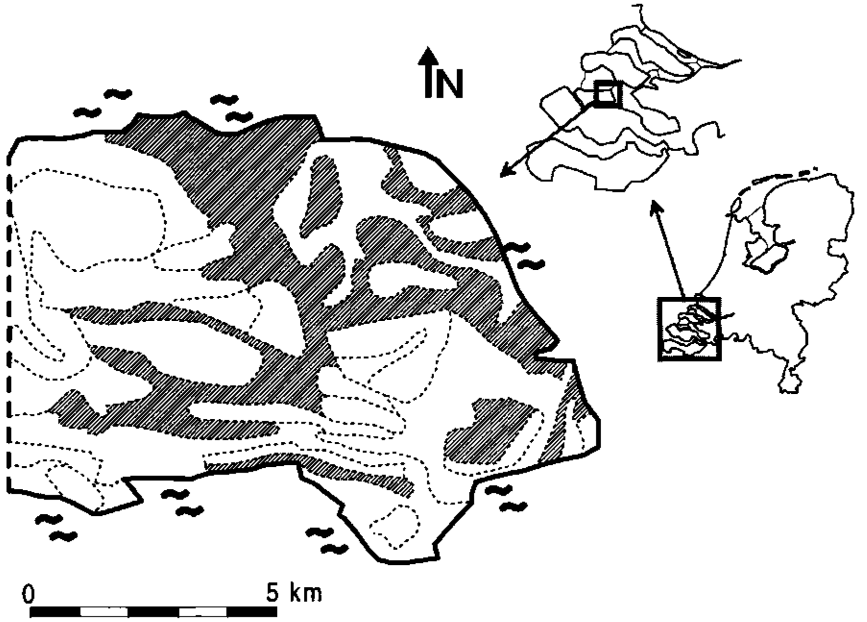

**Figure 7.1. Soil map of the study area in the southwestern part of The Netherlands (Pleijter et al., 1994). Areas belonging to the studied mapping unit (Mn25A) are hatched.**

Any study of sustainable land management faces a number of major problems: (i) agricultural production and production risks have to be evaluated for an extended period of time into the future; (ii) production is subject to often unspecified environmental restrictions which are to protect natural resources, and (iii) agro-ecological options are unacceptable when they are not viable from an economic or social point of view.

Field experiments, representing all possibilities for management, are not feasible because the required extensive experimentation would not only be too costly but would take too much time as well. A special role can be played here by exploratory simulation modeling of crop growth and nutrient fluxes, using validated models (e.g. Teng and Penning de Vries, 1992). Exploratory modeling can be used to define a range of management options from which the user can choose, realizing that any selection represents a compromise because different production and environmental requirements have to be balanced. Such options are strongly influenced by soil and climate conditions at any given location. In fact, we may assume that each soil series has a characteristic range of options, which may represent "windows of opportunity" as suggested by Bouma (1994). In this view, the genetically defined soil series would be a "geno-form", while results of different types of management would represent various "pheno-forms". These two terms are closely related to the well-known "genotype" and "phenotype" as used in the genetics discipline, where genotype is defined as "the genetic constitution of an organism or a group of organisms", and phenotype as "the observable physical or biochemical characteristics of an organism, as determined by both genetic makeup and environmental influences" (The American Heritage, 1992).

What is the specific input from pedologists in this sustainability research? Considering the decline in published pedology papers in recent years, the answer to the question "When the mapping is over, then what?" (Bouma, 1988) seems to be: "nothing". However, questions about sustainable land management can only be answered by integrating data and techniques such as: field survey, laboratory techniques, Geographic Information Systems, Remote Sensing and simulation modeling. The pedologist, who is by nature a synthesizing generalist, can, and should, play a crucial role in this.

Soil survey information is, so far, inadequately being used when developing sustainable management systems. Particular contributions could consist of: (i) providing soil data, including a variability assessment, which can directly or indirectly be used in simulation models (e.g. Finke et al., 1996), and (ii) providing patterns of occurrence of a given soil in landscapes allowing direct observation of the effects of particular types of management after different periods of time in terms of e.g. soil structure and organic matter content. A wide variety of "field experiments" is already there, waiting to be sampled and analyzed. In fact, a systematic inventory can also provide important information on the economic and social viability of various management systems.

The objective of this study is to explore use of soil survey information for developing sustainable management systems on a prime agricultural soil in the Netherlands, by: (i) distinguishing and characterizing different "pheno-forms", formed by different types of management, and (ii) analyzing the degree of sustainability by exploratory modeling.

# MATERIALS AND METHODS

## *Soils*

For one soil series in The Netherlands, a loamy mixed mesic Typic Fluvaquent (Soil Survey Staff, 1975), three different "pheno-forms", resulting from different types of farm management, were selected. Fig. 7.1 shows a fragment of the 1:50 000 soil map of the Netherlands, indicating the areas with the particular soil being studied (Mn25A according to the Dutch soil map, Pleijter et al., 1994). Field observations and interviews with farmers and extension specialists were made to identify the "pheno-forms". The first management type, abbreviated as *Bio*, has been managed for 70 years according to biodynamic principles (Reganold, 1995), which implies that no chemical fertilizer or chemical crop protection was utilized, but that soil quality was maintained by a favourable crop rotation and by use of organic fertilizer. Second type was the conventional (*Conv*) with a crop rotation of potatoes, grassland, sugarbeet and grains and use of agrochemicals. Soil tillage activities were comparable for *Bio* and *Conv*, and consist of ploughing in autumn to a depth of 25-30 cm as the main tillage activity. For *Bio* as well as for *Conv*, a two years old temporary grassland was selected which was part of the crop rotation used. The third management type was an old meadow (*Perm*), representing a soil structure with a more or less natural character. More detailed description of management types is presented by Droogers et al. (1996). Besides basic soil parameters like morphology, texture, organic matter, bulk density, and porosity, a comprehensive dataset of the soil hydraulic characteristics was obtained. As mentioned before, the soil map functioned as reference for selecting the "pheno-forms". Soil map units have their impurities. Field selection of a "pure" unit at a given site, was facilitated by using a flowchart to identify the map unit (Fig. 7.2).

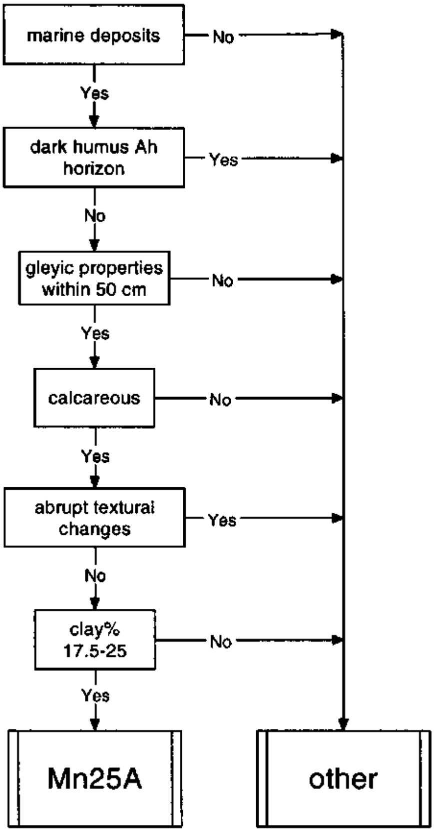

**Figure 7.2. Flowchart to determine the selected "geno-form" Mn25A, a loamy mixed mesic Typic Fluvaquent.**

In addition to the characterization of basic soil properties and the soil hydraulic properties, emphasis was put on the organic matter and nitrogen dynamics. Emphasizing N dynamics and ignoring other nutrients and agro-chemicals has two reasons. First of all, N is the limiting crop growth nutrient as other nutrients are sufficiently available in these fertile soils. Second, N is likely to be the dominant leaching component, because other biochemicals will be buffered and decomposed in these loamy soils.

Decomposition rates of organic matter was obtained by an incubation experiment during 33 days, with continuous $CO_2$ registration according to Nordgren (1988). A double exponential fit was performed on the decomposition rates (Deans et al., 1986):

$$C(t) = C_0 \cdot S \cdot (1 - e^{-k_1 \cdot t}) + C_0 \cdot (1 - S) \cdot (1 - e^{-k_2 \cdot t}) \tag{7.1}$$

where $C$ is the amount of decomposed organic carbon (g), $t$ is time (d), $C_0$ is potentially decomposable carbon (g), $S$ and (1-$S$) represent the labile and recalcitrant $C$ fractions decomposing at specific rates $k_1$ and $k_2$ ($d^{-1}$), respectively. Decomposition measurements during the first days of an experiment are mostly unrealistic (Rice and Havlin, 1994). For this reason, $S$ and $k_1$ were assumed to be fitting parameters. The applied simulation model for organic matter dynamics, to be described hereafter, distinguished two pools: an active "litter" pool and an less-active "humus" pool. The terms "litter" and "humus" should be considered in this context. The division between litter and humus pool was based on $C_0$. Decomposition rate for the litter pool was deduced from $k_2$, taking into account correction factors for the sample treatments air-drying (Sørensen, 1983) and sieving (Cabrera et al., 1994). Decomposition rates for the humus pool could not be deduced from this short-term experiment and were set at 0.00007 $d^{-1}$ (Vereecken et al., 1990b). This decomposition of humus was of minor importance as only one growing season was analyzed in this study.

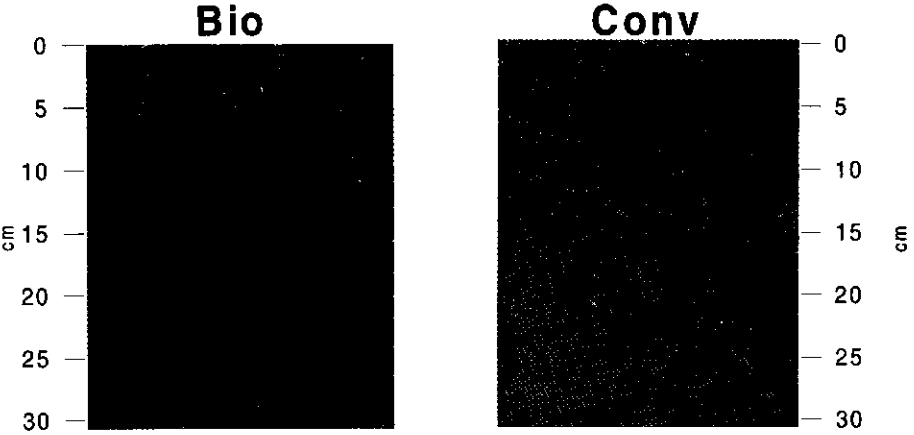

**Figure 7.3. Pictures of the topsoil of the two arable "pheno-forms" *Bio* and *Conv* (see Table 7.2).**

### *Simulation model*

Water, organic matter, solute and heat dynamics in soil, and crop growth, were simulated with an integrated mechanistic model. Several, well tested, modules were combined into the WAVE package (Vanclooster, 1994). Crop growth was simulated with SUCROS (Spitters et al., 1989), water dynamics with SWATRE (Feddes et al., 1978), organic matter and N dynamics according to Johnsson et al. (1987), solute transport with the convection-dispersion equation (Warrick et al., 1971) and heat transport with the general soil heat flow equation (Wagenet and Hutson, 1989). All submodules were thoroughly tested and validated (see references mentioned before). Model performance was tested in general by Diels (1994) and by Vanclooster (1995), and for this specific case by Droogers and Bouma (1996).

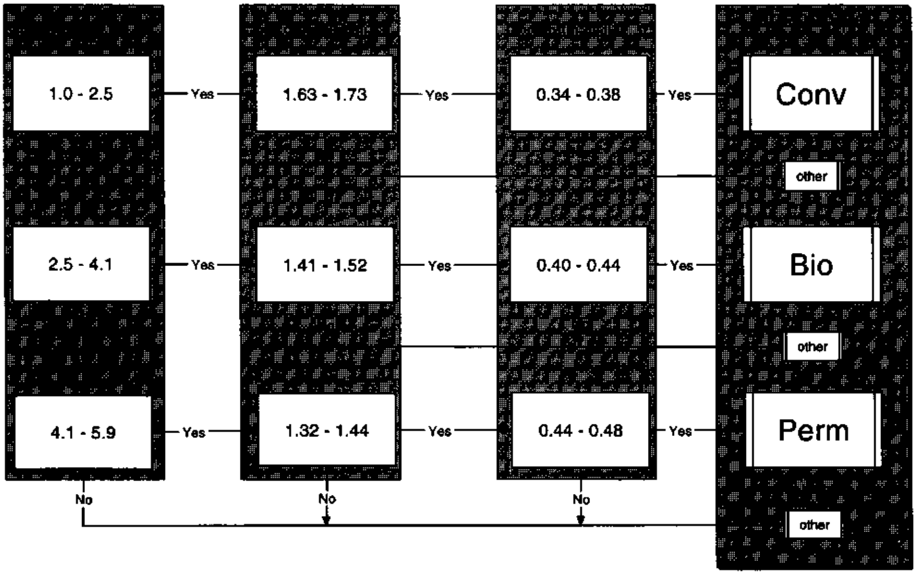

**Figure 7.4. Decision tree for determination of the three "pheno-forms", based on bulk density, organic matter and porosity of the topsoil, 10-30 cm.**

### *Sustainability scenarios*

Sustainability for the three "pheno-forms" was analyzed by defining four scenarios which were compared in terms of their productivity and N-leaching. The first scenario defined potential productivity, which is only determined by weather conditions: temperature, global radiation and potential transpiration. Results are soil independent and should be considered as a reference productivity, e.g. the maximum theoretically obtainable yield. The second scenario was based on the assumption that only water limits yield and no other limitations occur such as nutrient shortage, occurrence of diseases, or weed growth. For the third scenario currently applied management was considered, including fertilizing practices. This implies for *Bio* no chemical fertilizer but a manure application of 30 000 kg ha$^{-1}$ which corresponds with a plant-available N amount of 30 kg ha$^{-1}$. For *Conv* and *Perm* 130 kg N ha$^{-1}$ was applied as commercial fertilizer. The third scenario allows a comparison of measured and simulated yields and nutrient fluxes. The fourth and last environmental scenario was focused on reduced N-leaching to the groundwater. N concentrations in drinking water may not exceed 11.3 mg $l^{-1}$ (50 mg $l^{-1}$ nitrate) in the Netherlands. Concentrations are usually estimated by dividing total N-leaching during a year by the precipitation surplus in that same year. Simulations were focused on defining critical N fertilization rates that did not exceed this critical leaching rate.

All scenarios were calculated for one growing season with spring wheat as the crop for the three "pheno-forms". Weather has a significant influence on the processes of crop growth, organic matter dynamics and N-leaching. In order to take into account climatic effects, all scenarios were simulated with daily weather data of the last 30 years in the Netherlands.

**Table 7.1. Basic properties of the topsoil, 10-30 cm, for the three distinguished "pheno-forms" and their corresponding management types.**

| Field | Management | Bulk density | | Organic matter | | Porosity | |
|---|---|---|---|---|---|---|---|
| | | avg. | std. | avg. | std. | avg. | std. |
| | | — Mg $m^{-3}$ — | | —— % —— | | — $m^3$ $m^{-3}$ — | |
| Bio | biodynamic, temporary grassland | 1.47 b | 0.065 | 3.3 b | 0.59 | 0.42 b | 0.015 |
| Conv | conventional, temporary grassland | 1.68 c | 0.061 | 1.7 a | 0.05 | 0.36 a | 0.021 |
| Perm | conventional, permanent grassland | 1.38 a | 0.109 | 5.0 c | 0.57 | 0.46 c | 0.023 |

*Differences are significant at P = 0.05 if followed by different letters.*

**Table 7.2. Soil structure description of representative profiles of the three "pheno-forms".**

| Field | Depth | Shape | Size of peds | Grade |
|---|---|---|---|---|
| | cm | | | |
| Bio | 0-25 | prismatic, | coarse | moderate |
| | | subangular blocky | coarse | moderate |
| | 25-45 | prismatic, | coarse | strong |
| | | blocky | coarse | strong |
| | 45-50 | subangular blocky | coarse | moderate |
| Conv | 0-7 | subangular blocky | fine | strong |
| | 7-13 | blocky | fine | strong |
| | 13-50 | prismatic, | coarse | strong |
| | | blocky | coarse | strong |
| Perm | 0-15 | crumb | very fine | weak |
| | 15-30 | crumb/granular | fine | weak |
| | 30-50 | subangular blocky | medium | moderate |

# RESULTS AND DISCUSSIONS

## Soil characteristics

Brief descriptions of basic soil characteristics are presented in Table 7.1 and 7.2 and in Fig. 7.3. More detailed descriptions are presented by Droogers et al. (1996). Additionally to the "geno-form" flowchart (Fig. 7.2), a "pheno-form" decision tree was constructed (Fig. 7.4). Distinction between "pheno-forms" was based on the 99% confidence intervals for means of bulk density, organic matter and porosity.

Results from the decomposition experiment, combined with some literature data, as used in the nitrogen module of the simulation model, are presented in Table 7.3. The double exponential equation (eq. 7.1) provided an optimal fit of the observed C decomposition with $R^2$ values higher than 0.999. Decomposition rates were almost equal for *Bio* and *Conv*, and slightly higher for *Perm*. The amount of litter expressed as fraction of the total amount of organic matter was comparable for *Bio* and *Conv*, and lowest for *Perm*. However, absolute amounts of litter were highest for *Bio* followed by *Perm* and *Conv*. The amount of humus is less important as decomposition rates are low and simulations were only applied for a period of one year.

**Table 7.3. Decomposition rates (*k*) of organic matter, relative (*f*) and absolute sizes (*C*) of organic matter pools. $k_{hum}$ was deduced from Vereecken et al. (1990). Other values were obtained from the incubation experiment. *C/N* ratios account for the total organic matter pool.**

| Field | $k_{lit}$ | $k_{hum}$ | $f_{lit}$ | $C_{lit}$ | $C_{hum}$ | $C/N$ |
|---|---|---|---|---|---|---|
| | $d^{-1}$ | | - | Mg $ha^{-1}$ | | - |
| Bio | 0.00095 | 0.00007 | 0.070 | 4500 | 59700 | 9.2 |
| Conv | 0.00092 | 0.00007 | 0.066 | 2700 | 38300 | 8.9 |
| Perm | 0.00123 | 0.00007 | 0.036 | 3200 | 85700 | 9.1 |

**Table 7.4. Yields obtained for the different scenarios. All data represent the average obtained from simulations with 30 years of weather data.**

| Field | Potential | Water-limited | Current | EnvA | EnvB | EnvC |
|---|---|---|---|---|---|---|
| | kg $ha^{-1}$ | | | | | |
| Bio | 7766 a | 7404 a | 2887 a | 4240 b | 5264 b | 7019 b |
| Conv | 7766 a | 7344 a | 6822 b | 1975 a | 4163 a | 6300 a |
| Perm | 7766 a | 7375 a | 7250 b | - | 4481 a | 6755 ab |

*Differences are significant at $P = 0.05$ if followed by different letters.*

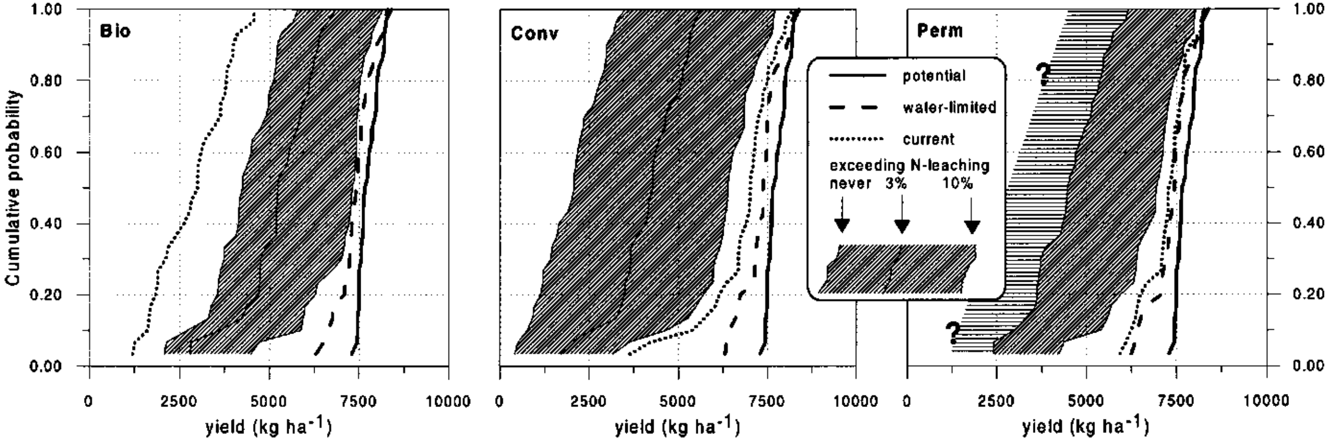

**Figure 7.5.** Cumulative probability function of simulated yields for the defined scenarios (see text). Probabilities were obtained by using 30 years of climatic data. The environmental scenario A, never exceeding N-leaching lower than 11.3 mg l$^{-1}$, was not reachable for Perm.

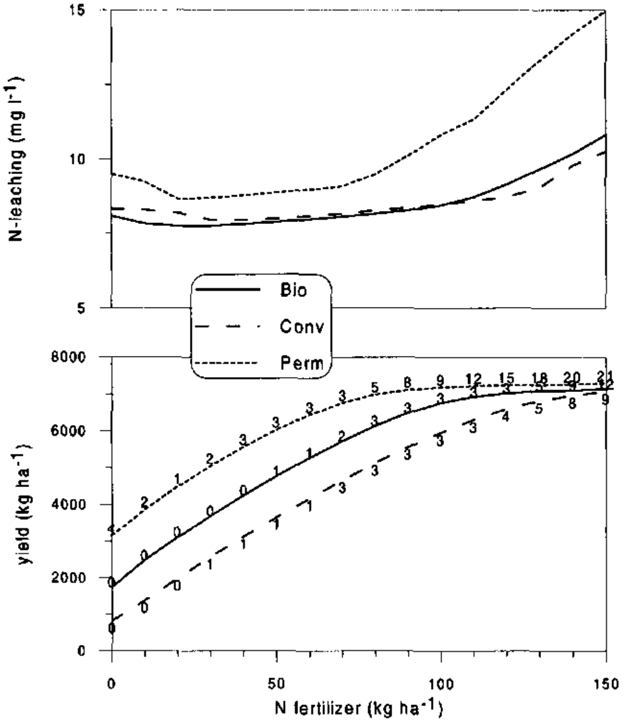

**Figure 7.6. Average yields and average N-leaching for different N applications. Numbers in the yield graph, indicates the number of years for a 30 years period when N-leaching exceeds 11.3 mg l$^{-1}$.**

### *Sustainability scenarios*

Potential productivities of the three "pheno-forms" were equal (Table 7.4), as only the weather conditions determine this yield. Differences in simulated yields for the 30 years of weather conditions were quite small (Fig. 7.5). The average water limited yield, scenario two, was about 5% lower than the average potential yield. This low reduction was caused by the relative insensitivity of wheat for drought.

For the third scenario (currently applied management), average yield for *Bio* was only 37% of potential yield, while yields for *Conv* and *Perm* were 88% and 93% of potential yield. These values correspond with values observed in the field. Despite the relative high amount of organic matter and the organic fertilizer for *Bio*, the N demand of the plant could not be satisfied. Nitrate leaching for current management was different for the three "pheno-forms". *Bio* never exceeded the 11.3 mg l$^{-1}$ N-leaching. *Conv* exceeded this limit in 16% of the years, while the corresponding value for *Perm* was 66% .

The environmental scenario was analyzed by simulating different amounts of fertilizer application and the associated yields and N-leaching. Simulations were again performed with 30 years of daily climatic data. Besides average N-leaching over 30 years, the probability of exceeding the critical N-leaching rate of 11.3 mg $l^{-1}$ in a year was analyzed. The pure effect of N-mineralization on yield can be seen when considering the zero fertilization level (Fig. 7.6). Yields for the "pheno-forms" with high organic matter contents, *Bio* and *Perm*, were higher than yields for *Conv*. It is also clear that fertilizer applications higher than 90 kg N $ha^{-1}$ do not result in a yield increase for *Perm*. A low N application can reduce N-leaching as compared with zero application. A small amount of N enhances plant growth, resulting in higher N-uptake and, consequently, less N-leaching.

The environmental scenario, focused on N-leaching never exceeding 11.3 mg $l^{-1}$, cannot be realized for *Perm*. Even with a low N application of 20 kg $ha^{-1}$ the critical amount of nitrate leaching was exceeded in one out of 30 years. Mineralization was high, but not in a period when N could be used by the crop. Productivity drops therefore substantially and N-leaching was still high. Two additional environmental scenario's were introduced next. EnvB: N-leaching exceeding 11.3 mg $l^{-1}$ may occur in one out of 30 years, and EnvC: N-leaching may exceed this critical amount in three out of 30 years. These less restrictive environmental scenarios have considerable effects on yield expectations (Fig. 7.5). They provide quantitative data on variation of nitrogen leaching as a function of time for policy makers to determine critical N-application rates. They will have to choose acceptable risks in terms of probabilities of exceedance.

# CONCLUSIONS

Sustainability can be analyzed by applying the presented data to the four indicators as defined by FAO (1993). Production levels (i), expressed here as spring wheat yield, can be found in Table 7.4 and Fig. 7.5. Production risks (ii) are presented as probability curves (Fig. 7.5). Environmental aspects (iii), here represented by the N-leaching, are also shown in Fig 5. The economic and social indicators (iv) are not explicitly discussed in this paper. However, the different scenarios allow a pro-active input into any economic and social analysis by defining the range of possibilities, the "window of opportunity". The presented data also give the opportunity to analyze the effects when indicators for yield and leaching have to be balanced. For example, for different production levels, the effect of fertilization on N-leaching can be predicted (Fig. 7.6).

Implications for using existing soil surveys, which are available in many countries, can be deduced from this study. Every map unit is representative for a given soil series (or associations of soil series), which we have considered in this paper to represent a "geno-form". Clearly, different types of management result in different types of soil behavior, which are characteristically different for each soil series. Additional field research within delineated areas of the soil map can result in defining a series of well defined "pheno-forms", each resulting from different management, which can be defined by interviewing farmers and extension workers. Measurement of basic hydraulic and chemical soil characteristics and use of simulation models for each "pheno-form" provides data for the particular soil series that dynamically expresses the degree of sustainability of the production system. This can be done because related expressions are obtained for yield, probabilities that certain yields are exceeded (risk) and the associated leaching rates. The latter are expressed in different degrees of rigidity to allow a selection by policy makers, of levels that are considered to be acceptable. This way, available soil survey information, in terms of soil map and soil data for soil series, can be used in an innovative manner.

## ACKNOWLEDGMENTS

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# Chapter 8

# SOIL QUALITY OF A DUTCH SOIL SERIES AS INFLUENCED BY LONG-TERM FARM MANAGEMENT PRACTICES

**Abstract** The sustainability analysis of land use is an important topic for soil in the next decade. A combined procedure using (i) soil survey information, (ii) management information, and (iii) organic matter content as a soil quality indicator, was used for a sustainability analysis. Organic matter contents and management information were obtained from fifteen fields in loamy, mixed, mesic, Fluvaquents in the Netherlands. Management, present and past, was defined in terms of five factors: tillage, crop rotation, chemical fertiliser, organic fertiliser and biocides. Results from interviewing farmers show that only four different management systems occurred: conventional arable, conventional grass, ecological arable and ecological grass. Organic matter contents were in the range from 1.7% to 5.0%. Crop rotation, i.e. arable or grass, affected organic matter contents, while conventional vs. ecological had no effect. A regression equation was developed to be used in a pro-active exploratory way to recommend management practices which may lead to a desired organic matter content. The presented methodology demonstrates the combined use of soil survey, management information, and soil quality indicators, in a sustainability analysis.

## INTRODUCTION

Defining sustainable forms of land use in order to maintain agricultural production in an environmental friendly manner, is the challange for the next decades (UNCED, 1992). We follow here the definition given by FAO (1993): "Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: (i) maintain and enhance production and services; (ii) reduce the level of production risk; (iii) protect the potential of natural resources and prevent degradation of soil and water quality; (iv) be economically viable and socially acceptable". Soils play a paramount role in the discussion concerning sustainability. Soil is one of the most important natural resources. People depend on the quality of their soil to grow their food and to serve as a living filter that purifies the wastes they produce. Therefore, soil scientists can, and should play a leading role in the discussion about sustainable management practices (Bouma, 1988). To take up this task a critical analysis of soil and a discussion about the direction in which soil should evolve, is needed. Restricting attention to soil survey and land evaluation, two important developments have occurred during the past decades. First, emphasis has been shifted from a descriptive methodology (i.e. producing soil maps and classification systems), towards a focus on the relevance of soils for society, i.e. the functioning of soils. Land evaluation, land quality, soil quality, land- and soil-indicators are keywords in the discussion on functioning of soils (among others, Karlen et al., 1997; Rossiter, 1996; Pieri et al., 1995). The second development is the conviction that a given soil series cannot be considered to have static properties, but that its management can have a considerable influence on these properties and therefore on sustainability of land utilisation types (Bouma, 1994). In this view, the genetically defined soil series can be denoted as a "geno-form", while "pheno-forms" indicate differences in soils within a particular geno-form as a result of different types of management (Droogers and Bouma, 1997).

These two developments in soil survey contribute towards the discussion on sustainable land management practices. Evaluation of the effects of existing management types and application of agro-ecological simulation models, provides the opportunity to define sustainable systems that balance requirements for agricultural production and environmental impact (e.g. Droogers and Bouma, 1997). This kind of analysis provides useful information about the sustainability of the described systems, but does not indicate how to reach the most desirable system and how long it will take. Setting up field experiments with a broad range of management types is not feasible, as it may take decades before a soil is in equilibrium with the applied management (Phillips and Phillips, 1984). Moreover, costs of such experimentation will be prohibitively high. However, such "experiments", admittedly under rather loosely defined conditions, are already being performed by farmers in their use of the land. Analysis of the effects of a broad range of farm management practices can supply this kind of information. A soil map can be used to identify areas where a particular soil series occurs, providing a relevant means of stratification. Different soil series are likely to show different behavioural patterns.

Soil quality is defined as (Karlen et al., 1997): "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation". Soil quality indicators can be used to characterise the accumulated effects of a series of land use systems that have been applied over a period of decades. These soil quality indicators describe the most significant information in summary form and are used as a means of communication. They can be "static" using soil parameters such as pH, bulk density, porosity, or "dynamic" using simulation models (Droogers and Bouma, 1996). In this study the "static" soil quality indicator organic matter content has been used. Organic matter can be considered as a relatively stable, integrating soil parameter, reflecting management practices over periods of decades. Organic matter contributes to a good soil structure and nutrient balance, when soils are properly managed.

In contrast to field studies, as suggested here, simulation models, such as CENTURY, can also be used to predict organic matter contents (e.g. Parton et al., 1992). These models provide reliable information for large-scale and long-term consequences of climate and management changes (Parton et al., 1988), but are unsuitable for short-term, i.e. years, and detailed management practices. Moreover, data-need for these models is enormous. Hassink and Whitmore (1997) presented a semi-empirical model to predict organic matter contents with a time scale from 1 to 20 year. However, input parameters are not defined and can only be quantified by "systematically varying parameters to produce good fits of the measured data" (Hassink and Whitmore, 1997). This is not attractive.

In this study we explore the potential of combining (i) soil survey information, (ii) farm management information, and (iii) the organic matter content as a soil quality indicator, to define sustainability. For one soil series (a loamy, mixed, mesic, Typic Fluvaquent) fields with different management practices were selected, using an existing 1:50 000 soil map. Management practices and organic matter contents were determined. Statistical procedures were used to evaluate the effect of management on organic matter content, and, most importantly, indicate which management practices should be performed in order to reach a particular organic matter content.

In summary, the objectives of this exploratory study for a prime agricultural soil in the Netherlands were to: (i) relate different management practices to the soil quality indicator "organic matter content", (ii) develop recommendations for management practices to reach a required organic matter content and (iii) deduce procedures to analyse the sustainability of different management systems.

## MATERIAL AND METHODS

Fields with different management practices were selected in the south-western part of the Netherlands. All fields were situated on the same soil series, a loamy, mixed, mesic, Typic Fluvaquent (Soil Survey Staff, 1975) or Mn25A according to the Dutch soil map 1:50 000 (Pleijter et al., 1994). This soil series covers about 100 000 ha in the Netherlands and is considered to be prime agricultural land. As soil maps have their impurities, each selected field was verified to be occupied by "pure" soil series.

Methodology to classify and evaluate farm management systems is still in development. The first attempt to develop a classification system for land evaluation, initiated by FAO (1976), has inspired many scientists to use and extend the system. This has resulted in a huge amount of definitions and abbreviations, e.g. Land Unit (LU), Land Use Type (LUT), Land Use System (LUS), Land Use System with a defined Technology (LUST), Land Mapping Unit (LMU), Land Characteristic (LC), Land Use Requirement (LUR), Land Quality (LQ), Evaluation Unit (EU), Land Evaluation Unit (LEU), Land Evaluation and Farming Systems Analysis (LEFSA) (e.g. Rossiter, 1996; Jansen and Schipper, 1995; FAO, 1976).

**Table 8.1. Distinguished management types based on the five factors. "Yes" referred to mostly, and "no" to almost never.**

| Management | Tillage | Crop | Chemical fertiliser | Organic fertiliser | Biocides |
|---|---|---|---|---|---|
| conventional arable | yes | arable | yes | no | yes |
| conventional grass | no | grass | yes | no | yes |
| ecological arable | yes | arable | no | yes | no |
| ecological grass | no | grass | no | yes | no |

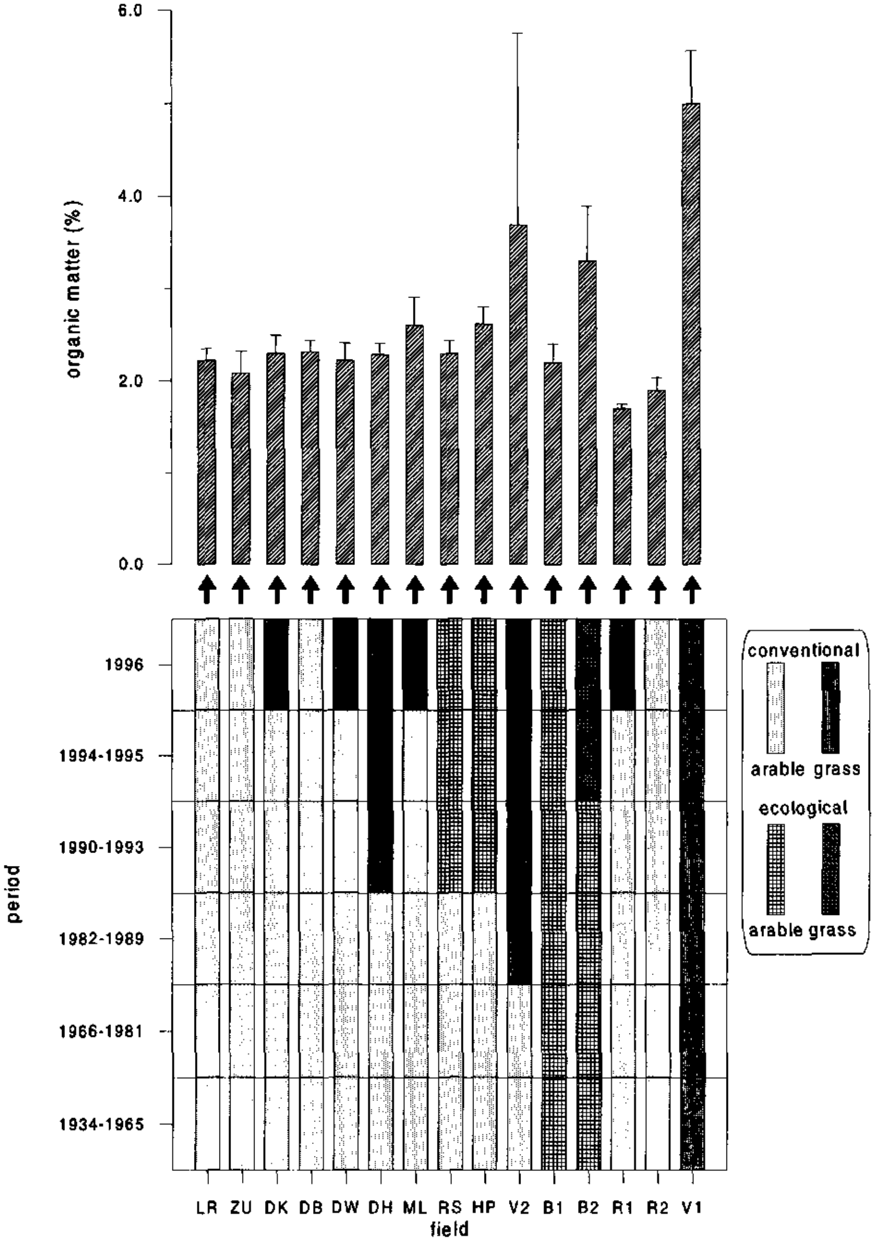

**Figure 8.1. Organic matter content (upper part) and corresponding management practices (lower part) for the 15 selected fields, covering the period 1934-1996.**

In this study we used a very simple, semi-quantitative description of management practices which can be obtained relatively easily by interviewing farmers. Five factors were selected, all related to activities that affect soil properties, especially soil organic matter content: (i) tillage, (ii) crop rotation, (iii) chemical fertiliser, (iv) organic fertiliser and (v) biocides (Table 8.1). As these five factors should be easily obtainable from information provided by farmers, the only quantification is provided by a "yes" or "no" answer, where "yes" indicates "mostly", and "no" indicates "almost never". For the factor "crop rotation" only the distinction has been made between arable crop and grass. More precise descriptions are likely to result in a huge amount of detailed data, which are not operational when relations with soil quality indicators should be established. We have therefore clearly focused on developing a very simple procedure. Besides quantifying the current management practices, also past management should be considered. It is assumed that recent management practices have more affect on soil properties than earlier practices. Therefore, each management factor was presented in periods of years, taking a quadratic function to determine the length of the periods: 1, 2, 4, 8, 16 and 32 years. In this way, management practices were defined in terms of five factors for six periods covering the last 63 years. For this period reasonably reliable information was available.

A total of 15 fields with different management types have been selected. More fields will be selected in follow-up studies for this and other soil series, but this exploratory study is intended to illustrate the procedure, rather than to provide a final result for the considered soil series. On each field, four plots were randomly selected and at two depths, 12 and 20 cm, samples of 100 $cm^3$ were taken, dried at 105°C, roots were picked out, and calcium carbonate removed by adding an excess of hydrochloric acid. Total carbon was then determined using an element analyser technique. Conversion from total carbon to organic matter content was made, assuming a factor 2 for the ratio organic matter to total carbon (Nelson and Sommers, 1982).

# RESULTS

## *Management*

The five factors to describe management can hypothetically be combined into 32 different combinations ($2^5$). After analysing all the information provided by farmers it appeared that many combinations did not exist, and the amount of management types could be reduced to only four (Table 8.1). As mentioned before, not only the current management type should be considered, but also historic management should be taken into account. Results of this analysis (Fig. 8.1, lower part) showed that conventional arable was the dominant management type for the 15 fields. Four fields, *RS*, *HP*, *B1* and *B2*, were managed ecologically, from which two, *B1* and *B2*, since 1924. During some periods, management was a combination of different management types, especially grass vs. arable. In this case the dominant land use type was used for the whole period. Furthermore, management practices from the period 1934-1965 were not always exactly known and, especially at the beginning of this period, should probably be considered as a mixture between conventional and ecological according to our classification system.

### Organic matter

Statistical analyses show that samples taken at 12 and 20 cm depth were not significantly different. ANOVA procedure resulted in a significance level of probability in F values of 0.17 and regression analysis resulted in $R^2$ of 0.16. Therefore, organic matter contents from these two depths have been combined.

Organic matter contents for the 15 fields ranged from 1.7% to 5.0% (Table 8.2 and Fig. 8.1 upper part). A multiple range test, applied on all the individual samples, using 90% Least Square Differences, yielded four homogeneous groups. *R1* and *R2* belonged to the group with the lowest organic matter contents of less than 2%, *B2* and *V2* were the highest group except one, while *V1* belonged to the highest group with 5% organic matter. Most fields were classified in the transition group AB, with organic matter contents in the range of 2.1% to 2.3%. Standard deviation for *V2* was very high with ranges in organic matter content among individual plots from 2.3% to 7.4%. No clear explanation could be found for this variation, except the lasting effects of arable use before 1982.

**Table 8.2. Organic matter contents for the 15 fields, as combind into four homogeneous groups according to multiple range test (90% Least Square Differences).**

| Group | A | | AB | | | | | | | | B | | C | | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Field | R1 | R2 | ZU | B1 | LR | DW | DH | DK | RS | DB | ML | HP | B2 | V2 | V1 |
| Organic matter (%) | 1.7 | 1.9 | 2.1 | 2.2 | 2.2 | 2.2 | 2.3 | 2.3 | 2.3 | 2.3 | 2.6 | 2.6 | 3.3 | 3.7 | 5.0 |
| Standard deviation | 0.05 | 0.14 | 0.24 | 0.21 | 0.13 | 0.19 | 0.12 | 0.19 | 0.14 | 0.12 | 0.31 | 0.19 | 0.59 | 2.07 | 0.57 |

### Organic matter vs. management

Management practices and their associated organic matter content are shown in Fig. 8.1. Management practices for all the fields during the two first periods, 1934-1965 and 1966-1981, were similar for each field and were therefore considered as being one period in further analysis. Periods were indicated as Y1 (1996), Y2 (1994-1995), Y4 (1990-1993), Y8 (1982-1989) and Y16 (1934-1981). Not all combinations of management vs. periods occurred. For example, ecological management followed by conventional management was not observed. Also, grass preceded by arable occurs frequently, but arable preceded by grass did not occur. This can be explained by economic developments and is also, partly, the result of the classification of management types in periods covering more years. Grass, as part of a crop rotation, was mainly grown for only one or two succeeding years, while classification was based on the dominant management type during the whole period.

First we will consider whether differences between conventional and ecological management are significant. A nested ANOVA procedure (Splus, 1995) showed that Y2, Y4 and Y16 could not be analysed as no changes in conventional and ecological have been occurred between these periods. Furthermore, ANOVA resulted in very high probabilities in F values for Y1 and Y8 (0.95 and 0.75 respectively) indicating that organic matter content was not related to conventional or ecological management. This contradicts results presented by Droogers and Bouma (1996), who reported that ecological management had resulted in higher organic matter contents (*B1* and *B2*) in comparison with a conventional system (*R1* and *R2*). However, they studied management systems which had existed for decades, guarantying that soil properties were in an equilibrium state with applied management. In this study also systems in transition have been included, e.g. *RS* and *HP*.

The nested ANOVA procedure has also been applied to analyse the effect of crops, i.e. arable or grass, on the organic matter content. Probabilities in F values for all periods were highly significant with values lower than 0.01, except period Y4 which had a probability in F value of 0.30. As the type of crop has such a significant influence on organic matter, a multiple regression equation was developed, excluding period Y4, yielding ($r^2 = 0.82$):

$$O.M. = 2.2 + 0.0 \cdot Y1 + 0.6 \cdot Y2 + 0.9 \cdot Y8 + 1.3 \cdot Y16 \tag{8.1}$$

where *O.M.* is organic matter content (%), and Y1 through Y16 equals 1 for grass and 0 for arable landuse for the considered period. This regression analysis shows clearly that grass increases the amount of organic matter in this particular soil series. However the 0.0 coefficient for period Y1, indicated that only one year of grass did not influence the organic matter content. The constant term of 2.2% can be considered as the average minimum organic matter content for this soil series.

## CONCLUSIONS AND DISCUSSION

This exploratory study showed that management, as defined here in broad terms, has a distinct effect on soil quality, taking organic matter content as an indicator. Crop rotation in this study affected organic matter significantly, while conventional vs. ecological had no effect on the organic matter content. Regression (Eq. 8.1) can be used in a pro-active way to recommend management practices in order to reach a desired organic matter content.

Previous studies showed that potential productivity of an ecological system, with higher organic matter contents, was higher than a conventional system, but the risk of compaction was higher as well (Droogers et al., 1996). High organic matter contents could also lead to high mineralization, inducing considerable risks of nitrate leaching (Droogers and Bouma, 1997). Therefore, besides the organic matter content as a soil quality indicator, additional, more focused indicators could be used. For example, Bouma and Droogers (1997) proposed the use of a soil quality indicator for production, considering risk of nitrate leaching and yield probability.

Implications for future research on sustainability in soil survey and land evaluation can be derived from this study. The following procedure is proposed: (i) Select the soil series of interest. (ii) Select soil quality indicators, relevant for sustainability. These can be "static" indicators, as applied in this study, or "dynamic" indicators. (iii) Select fields, where the given soil series occurs, with a broad range of management practices. (iv) Determine values for the soil quality indicators for the fields considered. (v) Interview farmers and classify current and past management practices in a simple way. (vi) Apply statistical procedures, ANOVAs and regression analysis, to relate management practices to the selected soil quality indicators.

This procedure will result in a sustainability analysis following the four points of FAO (1993). Production levels (point i) can be defined by information provided by farmers and by simulation modelling for the various pheno-forms (e.g. Droogers and Bouma, 1997) including the level of risk (point ii). Simulations can also be used to define critical leaching levels of agrochemicals that do not lead to degradation of land and water (point iii). As Droogers and Bouma (1997) have shown, critical leaching rates are different for the different pheno-forms. Producing a variety of agro-ecological landuse options provides the necessary information's to be used by farmers, planners and politicians to arrive at production systems that are socially and economically attractive (point iv).

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# GENERAL CONCLUSIONS

There is an increasing awareness that defining and quantifying sustainable forms of landuse is essential. Developing countries need to produce food for the continuously growing population, while developed countries experience environmental problems by high-input agricultural production systems. Quantifying differences in soil structures, resulting from different farm management practices, was used to analyse sustainability elements of the considered management systems. General conclusions from the entire study are described here, while detailed conclusions, deduced from the different parts of this study, can be found in the chapters concerned.

## *Methodology*

The methodology applied in this study is based on three main points: (i) study of existing fields managed by "normal" farmers instead of focusing on experimental plots; (ii) derivation of soil quality indicators by using simulation models; (iii) examination of the most relevant processes at the appropriate time and space scales.

The use of existing fields instead of experimental plots had the advantage that systems in operation for decades could be compared and that the different soil structures were the results of real farm management practices. Effects of different type of management was studied in soils belonging to one soil series. Differences observed were, therefore, not due to genesis or natural soil forming features.

Quantifying differences in soil structure by simulation models resulted in "dynamic" assessments, instead of only "static". In principle, dynamic assessments could also be obtained from long-term field measurements. However, such experiments will be very expensive and the number of scenarios to be studied can only be limited. Most important is that such field experiments depend on unpredictable weather conditions and should be performed for at least seven years to take this variation into account (Chapter 3).

Concentration on the most relevant processes and application of the appropriate time and space scales is essential. For example, bypass flow was less important for the considered soils, as continuous macro-pores were limited only to the topsoil (Chapter 5). An example of applying the appropriate spatial scale, was the result that averaging hydraulic characteristics for a given management type did not affect the transpiration ratio (Chapter 3). Appropriate time scale was tested, for example, by comparing temporal aggregation levels for nitrogen leaching (Chapter 4).

## *Management*

Differences in management have resulted in different soil structure types, which, in turn, affect aspects of sustainability of the systems. Management type *Perm*, the permanent grassland, representing a soil structure with a more or less natural character, has the highest moisture supply capacity. *Bio*, the biodynamic type where no agrochemicals are used, is second best in this context. The conventional management system, *Conv*, has the lowest moisture supply capacity (Chapter 1, 2, 3). Considering only a drying out situation under green-house conditions (Chapter 6), *Perm* has the highest accessibility of soil water, followed by *Conv* and *Bio*. Soils should not only deliver water for plant growth, but they should also be tilled and trafficked. The sequence from highest to lowest workability and trafficability is *Conv*, *Perm* and *Bio* (Chapter 2). Moreover, leaching of agro-chemicals towards the groundwater should be as low as possible. Taking nitrate as a tracer for this leaching, resulted in a high risk for *Conv* and significant lower risks for *Bio* as well as *Perm* (Chapter 4). However, leaching of nitrates is also influenced by the organic matter dynamics. Including these organic matter processes *Bio* has the lowest risk, followed by *Conv*. *Perm* has the highest risk in this context, as a result of the high organic matter content (Chapter 7).

Table 1 presents a generalised overview of the characteristics described above, for the three soil structures in terms of most and least favourable properties. There seems to be no overall "best" soil structure considering these five characteristics. *Perm* is "best" in terms of supplying water to support crop growth. *Conv* is "best" considering the opportunity for mechanisation. A low nitrogen leaching occurs for *Bio*, while leaching of agrochemicals in general is "best" for *Perm*.

**Table 1. Generalized overview of five characteristics expressing sustainability for the three soil structure types.**

| | Chapter | *Bio* | *Conv* | *Perm* |
|---|---|---|---|---|
| water dynamics to provide plant growth | 1, 2, 3 | o | - | + |
| soil water accessibility | 6 | - | o | + |
| workability and trafficability | 2 | - | + | o |
| leaching of agrochemicals | 4 | o | - | + |
| nitrogen leaching | 7 | + | o | - |

*+ indicates most favourable properties,* o *is in between and - indicates least favourable properties*

Implications for selecting the most appropriate management type can be deduced from these results in two ways. First, a selection can be made based on the most important objective. For example, a soil structure type as found under *Perm* should be aimed for when production is the prime objective. On the other hand, when nitrate pollution of the groundwater is a serious problem, one should select a *Bio* management type.

Instead of this rigid selection, a more balanced decision process is advocated, considering the processes that lead to the described characteristics. *Perm* seems to have the highest potential to be considered as the best soil structure (Table 1). Workability and trafficability for *Conv* was best because the soil was relatively compact, which is unfavourable for plant growth. A solution for *Perm* could be the use of modified machinery, such as low pressure tires and minimum or zero tillage. The high nitrogen leaching for *Perm* was mainly caused by high mineralization as a result of the relatively high amount of organic matter in the soil. Reducing the amount of organic matter while, simultaneously, maintaining the same soil structure in terms of water supply capacity, could resolve this problem. *Bio* satisfies this requirement for organic matter content but due to poor tillage practices soil structure was unfavourable with a relatively low accessibility. Better tillage conditions could impose to form the "ideal" soil structure.

### *Implications for future soil survey*

This study emphasises that soils belonging to one soil series cannot be considered to be similar, but that management applied has a significant influence on soil structure and the organic matter content and, consequently, on aspects of sustainability. Now that most soil surveys are completed, soil survey specialists could concentrate on characterising this range of soil structures for a given soil series, followed by quantifying the behaviour of these different soil structures by using simulation models (Chapter 7). In turn, recommendations can thus be derived as to which management practices should be performed in order to reach a desired soil structure (Chapter 8).

# SUMMARY

Methodology for defining sustainable land management practices is increasingly needed to overcome environmental problems and to maintain production potentials. From the large amount of definitions for sustainable management the following was used here: "Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously: (i) maintain or enhance production and services; (ii) reduce the level of production risk; (iii) protect the potential of natural resources and prevent degradation of soil and water quality; (iv) be economically viable and (v) socially acceptable". Indicators to quantify sustainability are used to analyse the effects of different management types on the soil structure within one soil series in the Netherlands, a loamy, mixed, mesic, Typic Fluvaquent. It is logical to concentrate on soil structure when evaluating and comparing the effects of different management practices as they reflect management practices at an integrated level. Comparison was focused on three soil structure types, formed by different management practices. (i) A biodynamic system (*Bio*) where no chemical crop protection or commercial fertiliser has been applied since 1924. Animal manure and a crop rotation system with clover are intended to supply the required nutrients. (ii) A conventional system (*Conv*) representing a management system that is most common in the region. (iii) A system which has been permanently meadow since 1947 (*Perm*).

The biodynamic and conventional system were compared by converting "static" soil parameters, like organic matter content, bulk density, hydraulic characteristics, into a "dynamic" assessment by using a simulation model to calculate water-limited productivity. A thorough soil characterisation was made, including morphological and physical characterisation as well as monitoring of soil water contents and groundwater levels. Results of the comparison between simulated and measured moisture contents were such that the model was considered to be adequately validated. The simulated water-limited productivity for potatoes was significantly higher for the biodynamic system, indicating a favourable effect of the higher organic matter content. (Chapter 1)

Modern mechanised agricultural practices require soils to be able to be subjected to tillage and traffic, without adverse effects on soil structure. Threshold values for workability and trafficability were obtained for the three management types. Workability by the Atterberg test, trafficability by penetrometer measurements and an additional field-traffic experiment. Threshold values for *Conv* were most favourable, i.e. during relatively wet conditions *Conv* could still be tilled and trafficked. Periods of workability and trafficability were obtained by combining measured threshold values with simulated moisture contents. *Conv* had the longest workable and trafficable period in a year followed by *Perm* and *Bio*, respectively. (Chapter 2)

Applying appropriate spatial and temporal scales is essential in quantifying sustainability. The appropriate spatial scale was analysed by comparing the effect of averaging hydraulic characteristics of each management type. The required temporal scale, i.e. how many years should an experiment be continued so as to minimise effects

of weather variation, was studied by using 30 years of historical weather data. The ratio between simulated actual and potential transpiration was analysed for these 30 years. Results show that averaging hydraulic characteristics within each management type does not yield significant differences in comparison with using individual point data followed by averaging. The simulated transpiration ratios of the 30 years of weather data indicate that the length of an experiment should be at least seven years to significantly reduce the effect of the variable weather conditions. (Chapter 3)

Another temporal scale problem is related to the leaching of pollutants towards the groundwater, i.e. the definition of the time-aggregation level over which critical threshold values should be considered. Simulated nitrogen leaching was compared for the three management types at different time-aggregation levels, ranging from one day till 30 years. Leaching of nitrogen was highest for *Conv* followed by *Bio* and *Perm*, respectively. A clear double-log relationship exists between aggregation level of nitrogen leaching and the number of time elements during which the threshold value was exceeded. The appropriate aggregation level will have to be based on the travel time from the groundwater below the considered area to the drinking well. (Chapter 4)

Macro-porosity of the three management types, was quantified by staining technique combined with digital processing. This study was made to investigate occurrence of bypass flow which invalidates simulations assuming soils to be isotropic. Each of the 55 measured staining patterns was quantified by 17 different parameters defined in terms of size, shape and distribution. Continuous macro-pores were mainly restricted to the topsoil for the three management types. Factor analysis shows that the most important factor, the "total pore quantity", was similar for the three fields but had a clear depth effect. Factor two and three, the "individual pore quantity" and the "shape", were influenced by the applied management. (Chapter 5)

A key aspect in defining sustainable land management is the capacity of a soil to supply roots with water and nutrients. The concept water "availability" implicitly assumes all soil water to be "accessible" which may not be the case in coarse structured soils such as occur in *Bio* and *Conv*. A transpiration experiment with barley, using 15 undisturbed 6 $dm^3$ soil cores, showed that *Perm* had the highest supply capacity followed by *Conv* and *Bio*, respectively. The "rooting pattern characteristic" combined with the "water supply characteristic" was used to quantify the accessibility of soil water. Accessibility was highest for *Perm* and *Conv*, and lowest for *Bio*. (Chapter 6)

The genetically defined soil series, a "geno-form", can have various "pheno-forms" as a result of different management practices. Each "geno-form" will therefore have a characteristic range of soil structures, which was quantified by a dynamic simulation model. Four scenarios were quantified for the three "pheno-forms" based on productivity and nitrogen leaching towards the groundwater. Results illustrate that environmental regulation can be based on "acceptable" risks and that soil series (geno-forms), cannot be evaluated with a representative soil profile in specific field-level studies. (Chapter 7)

An extensive field survey, within one soil series, was performed to relate farm management practices, present and past, with organic matter contents. From the 15 analysed management practices a regression equation was developed which can, in turn, be used to recommend management practices which are likely to lead to a desired organic matter content. This exploratory study shows the combined use of soil survey and management information in defining a soil quality indicator represented here by the organic matter content. (Chapter 8)

Soil survey could focus in future on defining sustainable forms of landuse, considering that soils within one soil series are not similar. Farm management information combined with quantifying the associated soil structure types by simulation models, can form the basis for defining sustainable management systems for the soil series being studied. As many soil surveys are completed all over the world, the proposed procedure appears to be a worthwhile continuation of the rich tradition of soil survey research.

# SAMENVATTING

Het oplossen van milieuproblemen en handhaven van produktieniveaus leidt tot een toenemende behoefte aan methoden om duurzame vormen van landgebruik te definiëren. Uit de grote hoeveelheid bestaande definities voor duurzaam landgebruik is de volgende hier aangehouden: "Duurzaam landgebruik combineert technieken, beleid en activiteiten gericht op het integreren van sociologische en economische principes, rekening houdend met het milieu, om gelijktijdig: (i) produktie en gebruik te handhaven of te verbeteren, (ii) risico's in produktie te verminderen, (iii) natuurlijke rijkdommen te beschermen en degradatie van bodem- en waterkwaliteit te voorkomen, (iv) economisch levensvatbaar, en (v) sociaal acceptabel te zijn". Om de duurzaamheid te kwantificeren zijn indicatoren gebruikt die het effect van verschillende soorten management op de bodemstructuur, binnen één bodemtype in Nederland (Mn25A, kalkrijke, zware zavel, poldervaaggrond), te bepalen. Aangezien de bodemstructuur een totaalbeeld geeft van de effecten van het toegepaste management, is het logisch deze te gebruiken om verschillende soorten management te evalueren en te vergelijken. Deze vergelijkingen waren hoofdzakelijk gebaseerd op drie bodemstructuren. (i) Een biologisch-dynamisch systeem (*Bio*) waar al sinds 1924 geen chemisch gewasbeschermingsmiddel of kunstmest wordt gebruikt. Het gebruik van organische mest en een gewasrotatie met klaver, leveren de benodigde nutriënten. (ii) Een conventioneel systeem (*Conv*) dat vergelijkbaar is met het algemeen gangbare management zoals toegepast in de regio. (iii) Een systeem dat al sinds 1947 een permanent grasland heeft (*Perm*).

Het biologisch-dynamisch systeem en het conventioneel systeem zijn vergeleken door "statische" bodemeigenschappen, zoals organische stof, dichtheid en hydraulische eigenschappen, te vertalen in een "dynamische" beoordeling. Hiervoor is de water-beperkende opbrengst gekozen, welke is berekend met een simulatiemodel. Een uitgebreide bodembeschrijving werd uitgevoerd, bestaande uit een morfologische en fysische beschrijving, bovendien werden vochtgehalten en grondwaterstanden regelmatig gemeten. De vergelijking tussen gemeten en gesimuleerde bodemvochtgehalten waren goed, zodat het simulatiemodel betrouwbaar werd geacht. De gesimuleerde water-beperkende produktie voor aardappels was hoger voor *Bio* dan voor *Conv*, wat duidde op het gunstige effect van organische stof. (Hoofdstuk 1)

De moderne, gemechaniseerde landbouw heeft behoefte aan een bodem die bewerkt en bereden kan worden, zonder negatieve effecten op de bodemstructuur. Voor de drie managementtypen zijn grenswaarden bepaald voor bewerkbaarheid en berijdbaarheid. De Atterbergse methode is gebruikt voor de bewerkbaarheid en de penetrometer voor de berijdbaarheid. Verder is berijdbaarheid nog bepaald door een aanvullend berijdingsexperiment in het veld. Drempelwaarden voor *Conv* waren het gunstigst, wat inhoudt dat *Conv* onder relatief natte omstandigheden nog steeds bewerkt en bereden kan worden. De perioden waarop velden bewerkt en bereden kunnen worden, zijn bepaald door de gemeten drempelwaarden te combineren met gesimuleerde vochtgehalten. *Conv* bleek de langst bewerkbare en berijdbare periode te hebben, gevolgd door achtereenvolgens *Perm* en *Bio*. (Hoofdstuk 2)

Het toepassen van de juiste ruimte- en tijdschaal is essentieel wanneer duurzaamheid gekwantificeerd moet worden. Het effect van het middelen van de hydraulische eigenschappen voor elk managementsysteem, werd gebruikt om de juiste ruimteschaal te bepalen. De juiste tijdschaal, met andere woorden: hoeveel jaar moet een experiment duren om het effect van de variabele weersomstandigheden klein te houden, werd bepaald met behulp van 30 jaar weersgegevens. De verhouding tussen gesimuleerde actuele verdamping en potentiële verdamping is vastgesteld voor deze 30 jaar. Het gebruik van gemiddelde hydraulische eigenschappen per managementtype leidde niet tot significante verschillen in vergelijking met het gebruik van punt-eigenschappen gevolgd door middelen. De gesimuleerde relatieve verdampingen, bepaald met de weersgegevens over 30 jaar, geven aan dat een experiment minstens 7 jaar moet duren om het effect van deze variabele weersgegevens te minimaliseren. (Hoofdstuk 3)

Een ander tijdschaal-probleem heeft betrekking op de uitspoeling van verontreinigingen naar het grondwater. Het is met name van belang op welke tijdschaal drempelwaarden voor uitspoeling betrekking hebben. Er is een vergelijking gemaakt van de gesimuleerde stikstof-uitspoeling voor de drie managementtypen op tijdschalen variërend van één dag tot 30 jaar. *Conv* gaf de hoogste uitspoeling, gevolgd door *Bio* en *Perm*. Er blijkt een dubbel logaritmische relatie te bestaan tussen de tijdschaal waarop de stikstof-uitspoeling werd bekeken en het aantal malen dat de drempelwaarde werd overschreden. De juiste tijdschaal zou bepaald moeten worden aan de hand van de transporttijd van het grondwater onder het betreffende gebied naar het drinkwater-onttrekkingspunt. (Hoofdstuk 4)

Macroporiën van de drie managementtypen zijn gekwantificeerd met behulp van kleur patronen en digitale verwerkingstechnieken met het doel te bepalen of simulatiemodellen uitgaande van isotropie gebruikt kunnen worden. De 55 gemeten kleurpatronen werden gekwantificeerd met behulp van 17 verschillende eigenschappen, welke de grootte, de vorm en de verdeling van de macroporiën beschrijven. Doorgaande macroporiën werden bijna alleen maar aangetroffen in de bovengrond. Factoranalyse toonde aan dat de belangrijkste factor, de "totale hoeveelheid poriën", gelijk is voor de drie velden, maar dat er een duidelijk diepte-effect aanwezig is. De factoren twee en drie, de "individuele porie grootte" en de "vorm", worden wel beïnvloed door het management. (Hoofdstuk 5)

Een belangrijk aspect van duurzaam bodemgebruik is het vermogen van een bodem om plantenwortels te voorzien van water en nutriënten. Het concept van "beschikbaar" water gaat er vanuit dat al het bodemwater ook "toegankelijk" is. Dit zal met name niet het geval zijn voor gestructureerde bodems zoals bij *Bio* en *Conv*. Een verdampingsexperiment met gerst, gebruikmakend van 15 ongestoorde bodemmonsters van 6 $dm^3$, toonde aan dat *Perm* het meeste water kan aanleveren, gevolgd door *Conv* en daarna door *Bio*. Een combinatie van de "wortelpatroon-karakteristiek" en de "waterlevering-karakteristiek" werd gebruikt om de "toegankelijkheid" te bepalen. De "toegankelijkheid" is het hoogst voor *Perm* en *Conv*, en het laagst voor *Bio*. (Hoofdstuk 6)

Genetisch ingedeelde bodemtypen, de zogenaamde "geno-type", kunnen bestaan uit verschillende "feno-typen" die gevormd zijn als gevolg van verschillende typen management. Elk "geno-type" bestaat daarom uit een aantal verschillende bodemstructuren, welke gekwantificeerd werden met behulp van een simulatiemodel. Productiviteit en stikstof-uitspoeling naar het grondwater werden bepaald voor de drie "feno-typen" aan de hand van vier scenario's. De resultaten laten zien dat regelgeving op het gebied van milieu gebaseerd moet zijn op "aanvaardbare" risico's. Bovendien blijkt dat bodemtypen (geno-typen) niet kunnen worden beoordeeld aan de hand van een representatief profiel indien het studies op veldniveau betreft. (Hoofdstuk 7)

Binnen één bodemtype is een uitgebreide veld-inventarisatie uitgevoerd om een relatie te leggen tussen het, zowel huidige als vroegere, landbouwmanagement-systeem en de hoeveelheid organische stof. Een regressievergelijking werd opgesteld met behulp van de 15 bestudeerde systemen. Deze vergelijking kan ook gebruikt worden om adviezen te geven omtrent het te volgen management om zodoende het gewenste organische stofgehalte te bereiken. Deze verkennende studie laat zien hoe het gecombineerd toepassen van bodemkartering en informatie over management gebruikt kan worden om de bodemkwaliteit, hier uitgedrukt als het organische stofgehalte, te bepalen. (Hoofdstuk 8)

Bodemkartering in de toekomst zal zich met name moeten toeleggen op het definiëren van duurzame vormen van landgebruik, rekening houdend met het feit dat bodems binnen één bodemtype niet gelijk zijn. Informatie over landbouwmanagement, gecombineerd met het kwantificeren van de bijbehorende bodemstructuur, moet de basis leggen voor het definiëren van duurzame vormen van landgebruik binnen het bestudeerde bodemtype. Aangezien er wereldwijd vele bodemkarteringen zijn voltooid, zal de voorgestelde procedure een aanvulling kunnen zijn op de rijke traditie van het onderzoek in de bodemkartering.

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# Curriculum vitae

Peter Droogers (Leiden, 1961) volgde van 1978 tot 1981 de Middelbare Bosbouw en Cultuurtechnische School te Velp. Na zijn militaire diensttijd en diverse werkzaamheden (uitvoerder waterwerken bij slotgrachten, toezichthouder iepziekte-bestrijding, opzichter beheersovereenkomsten) kwam hij als terreinbeheerder bij Staatsbosbeheer in dienst.

Na twee jaar besloot hij deze werkzaamheden te staken en begon in 1985 de studie Hydrologie en Waterbeheer aan de Internationale Agrarische Hogeschool Larenstein te Velp. Tijdens zijn praktijktijd verrichtte hij toegepaste landbouw en irrigatie werkzaamheden in Portugal. Bij het Staringcentrum in Wageningen studeerde hij af op de koppeling van een oppervlakte- en grondwatermodel.

In 1989 rondde hij deze studie af en kwam in dienst bij de vakgroep Waterhuishouding van de Landbouwuniversiteit Wageningen. Gedurende vier jaar hield hij zich bezig met projecten gericht op de interactie tussen vegetatie, atmosfeer en landoppervlak met nadruk op bodem en water. Gedurende deze periode werkte hij mee aan internationale meet campagnes in Spanje (1991) en Niger (1992).

In 1993 trad hij in dienst bij NWO (Nederlandse organisatie voor Wetenschappelijk Onderzoek) en werd gedetacheerd bij de sectie Bodemkunde en Geologie van de Landbouwuniversiteit te Wageningen. Hij kreeg een aanstelling van vier jaar met als onderzoeksonderwerp het kwantificeren van bodemstructuren welke ontstaan als gevolg van verschillen in management.