QUALITATIVE AND QUANTITATIVE PHYSICAL LAND EVALUATION:

AN OPERATIONAL APPROACH

Promotor: dr.ir. J. Bouma
hoogleraar in de bodeminventarisatie en landevaluatie,
speciaal gericht op de (sub)tropen

Henny A.J. van Lanen

QUALITATIVE AND QUANTITATIVE PHYSICAL LAND EVALUATION:

AN OPERATIONAL APPROACH

Proefschrift
ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
dr. H.C. van der Plas
in het openbaar te verdedigen
op dinsdag 18 juni 1991
des namiddags te vier uur in de Aula
van de Landbouwuniversiteit te Wageningen.

Aan mijn ouders en Carla

STELLINGEN

1. De gemengde kwalitatieve/kwantitatieve fysieke landevaluatiemethode bespaart tijd doordat de toepassing van proces-georiënteerde simulatiemodellen kan worden beperkt tot de evaluatie van uitsluitend veelbelovende gebieden.
(Dit proefschrift).

2. De toevoeging "kwantitatief" aan fysieke landevaluatiemethoden zou moeten worden gereserveerd voor methoden uitgaande van proces-georiënteerde simulatiemodellen.
(Dit proefschrift).

3. De bewering dat kwalitatieve landevaluatiemethoden van weinig waarde zijn voor bevolkte, geïndustrialiseerde landen (Dent & Young, 1981) is onterecht.
Dent, D. & Young, A. 1981. Soil Survey and Land Evaluation. George Allen & Unwin, London, 278 pp.
(Dit proefschrift).

4. De gestelde noodzaak om proces-georiënteerde simulatiemodellen in de toepassingsfase nog uitgebreid te calibreren en te valideren (o.a. Feyen, 1987) geldt niet voor de landevaluatie omdat de hierbij de aandacht primair wordt gericht op potentiële situaties.
Feyen, J. 1987. Field validation of soil water and crop models. In: J. Feyen (Ed.), Simulation models for cropping systems in relation to water management, Commission of the European Communities, Luxembourg, EUR 10869, pp. 105-131.
(Dit proefschrift).

5. Zolang machine-bodem-gewas modellen nog niet operationeel zijn voor de kwantificering van bodemdegradatie en -regeneratie (Hadas et al., 1988) zijn geparametriseerde bodemstruktuurtypen in combinatie met bodem-gewas modellen een goed alternatief.
Hados A., Larson, W.E. & Allmaras, R.R. 1988. Advances in modelling machine-soil-plant interactions. Soil & Tillage Res. 11: 349-372.
(Dit proefschrift).

6. De positieve beoordeling van vergroting van de bewortelbare diepte door verbetering van het bodemprofiel gaat voorbij aan de verslechtering van het vochtleverend vermogen van de grond voor éénjarige, laatontwikkelende gewassen in groeiseizoenen met een droge eerste helft.
(Dit proefschrift).

7. Toepassing van kwalitatieve landevaluatie voor uitgestrekte gebieden, gericht op de inschatting van het produktie-potentieel, waarbij geen rekening wordt gehouden met verschillen in het potentiële produktieniveau tussen agro-klimatologische zones (o.a. Lee, 1987) leidt tot onvergelijkbare resultaten (FAO, 1978).
FAO 1978. Report on the agro-ecological zones project. World Resources Report 48, Rome, 158 pp.
Lee, J. 1987. European land use and resources. An analysis of future EEC demands. Land Use Policy 4: 179-199.
(Dit proefschrift).

8. De geïntegreerde modelbenadering voor de evaluatie van de effekten van ontwatering op de opbrengst van akkerbouwgewassen (Van Wijk et al., 1988) gebruikt voor de onderrandvoorwaarde gegevens die slecht aansluiten bij de gangbare verzameling van bodemkundige en hydrologische gegevens voor landinrichtingsprojekten.
Van Wijk, A.L.M., Feddes, R.A., Wesseling, J.G. & Buitendijk, J. 1988. Effect van grondsoort en ontwatering op de opbrengst van akkerbouwgewassen, ICW rapport 31, Wageningen, 130 pp.
(Dit proefschrift).

9. De potentiële gewasopbrengst is behalve van het klimaat en het gewas ook afhankelijk van de bodem (Feddes & Van Wijk, 1990) en zou als zodanig ook gedefinieerd moeten worden.
   Feddes, R.A. & Van Wijk, A.L.M. 1990. Dynamic land capability model: a case study. Philosophy Transactions Royal Society London B 329: 411-419.
   (Dit proefschrift).

11. De aloude opvatting in het Westland dat bepaalde tuinbouwgewassen voldoende hebben aan een goede bovengrond, terwijl de ondergrond weinig ter zake doet, en dat een goede bovengrond door verbetering wel gemaakt kan worden (Van Liere, 1948) vormt waarschijnlijk de voedingsbodem voor de substraatteelt ('soil-less cultures') in de glastuinbouw.
    Van Liere, W.J. 1948. De bodemkartering in het Westland. Boor & Spade, pp. 58-62.

12. Vrijwel alle mensen die zijn gedwongen uit een organisatie te vertrekken na een arbeidsproces van tientallen jaren ondergaan een rouwproces (Bruijnen, 1990); het is een diepe ervaring van verlaten zijn, stilstaan bij herinneringen uit het verleden, terugdenken, terugverlangen, het verlies ontkennen, boos en opstandig zijn, emoties tonen en tenslotte de acceptatie.
    Bruijnen, T. 1990. Rouwbegeleiding. Opbouw, 84 (5): 10-11.

13. Het onderzoeksmodel gebaseerd op voorwaardelijk of extern gefinancierd onderzoek, waarbij veelvuldig onderzoekers met een tijdelijk kontrakt worden ingezet, draagt niet bij aan de continuïteit en diepgang van wetenschappelijke kennis.

14. De aanduiding 'Europese Gemeenschappen' in plaats van 'Europese Gemeenschap' in vele officiële publikaties is ongelukkig met het oog op de eenwording van de EG in 1992, maar geeft in een aantal opzichten wel de actuele situatie weer.

15. Uit de afkorting SIG in het Frans en GIS in het Engels, Duits en Nederlands voor geografisch informatiesysteem zou men ten onrechte kunnen afleiden dat de talen zich aan elkaar spiegelen.

16. Leidinggevenden die uitsluitend op grond van hun hiërarchische positie besluiten kunnen nemen, hebben baat bij bestuurservaring in organisaties die vrijwel volledig uit vrijwilligers bestaan.

Stellingen behorende bij het proefschrift van H.A.J. van Lanen: Qualitative and quantitative physical land evaluation: An operational approach.

Wageningen, 18 juni 1991.

WOORD VOORAF

Het hier gepubliceerde onderzoek kon alleen maar tot stand komen door de steun die ik van velen direct en indirect heb mogen ontvangen.

Mijn belangstelling voor het onderzoeksveld van de landevaluatie werd gewekt tijdens mijn doctoraalonderzoek aan de toenmalige Landbouwhogeschool, dat begeleid werd door Prof.dr.ir. L.J. Pons, Prof.dr.ir J. Bennema, Dr.ir R. Brinkman en Dr.ir. J.S. Veenenbos. Mijn voormalige RID/RIVM collega's hebben mij geleerd om te gaan met de vele mogelijkheden van de computertechnologie, met name met de ontwikkeling en toepassing van proces-georiënteerde simulatiemodellen. Deze kennis vormde een zeer vruchtbare basis voor het onderzoek naar een verdere ontwikkeling van de landevaluatiemethoden, dat in samenwerking met mijn promotor Prof.dr.ir. Johan Bouma, destijds adjunt-directeur van de Stichting voor Bodemkartering, is uitgevoerd. Tijdens intensief onderzoek en inspirerend overleg heeft hij mij getoond hoe fragmentarische kennis kan worden aangevuld en geïntegreerd tot een samenhangend geheel. Het doet mij groot genoegen dat onder zijn zeer stimulerende begeleiding en zijn nimmer aflatende aandacht, dit geheel kon uitgroeien tot het onderhavige proefschrift.

Dr. David G. Rossiter, Cornell University (New York, VS) heeft mij geattendeerd op de mogelijkheden die geautomatiseerde kennissystemen hebben voor de verdere ontwikkeling van landevaluatiemethoden en heeft mij geholpen met de technische implementatie.

Het landevaluatie-onderzoek, dat een sterk integrerend karakter heeft, kan niet worden uitgevoerd zonder een intensieve samenwerking met vele collega's. Mijn mede-auteurs Manno Bannink, Obbe Boersma, Johan Bouma, Arnold Bregt, Jan-Dirk Bulens, Kees van Diepen, Willy de Groot, Mirjam Hack-ten Broeke, Free de Koning, Gert-Jan Reinds, Tom van Stiphout en Frans Wopereis hebben in het bijzonder bijgedragen aan één of meer onderdelen van dit proefschrift. Mirjam Hack-ten Broeke en Kees van Diepen hebben bovendien een aantal algemene hoofdstukken kritisch doorgelezen. Gerard van Soesbergen en Wim van der Voort hebben in verschillende fasen van het onderzoek steun verleend. Hun bereidwilligheid, steun en opbouwende kritiek was onontbeerlijk voor de totstandkoming van dit proefschrift. De medewerkers van de voormalige afdeling Bodemgebruik hebben mij vertrouwd gemaakt met de verschillende methoden van bodemgeschiktheidsinterpretatie die in de loop van de tijd zijn ontwikkeld door de voormalige Stichting voor Bodemkartering. Vele collega's van de Stichting voor Bodemkartering ben ik dankbaar voor de opfrissing en de vergroting van mijn bodemgeografische kennis na mijn komst van het RIVM.

De directie van de voormalige Stichting voor Bodemkartering en van het huidige Staring Centrum wil ik bedanken voor de mogelijkheden die zij mij boden om dit onderzoek uit te voeren en te publiceren. Voor de stimulerende invloed van de hoofdafdelingshoofden Dr. Jan Klijn in de beginfase, en Ir. Ben van der Pouw in het verdere verloop van het promotieonderzoek ben ik dankbaar. Laatstgenoemde heeft daadwerkelijk de faciliteiten gecreëerd voor de totstandkoming van dit proefschrift en was een kritisch lezer van het grootste gedeelte van de eindteksten. Het is plezierig dat onderzoek dat het instituutsbelang dient, tegelijkertijd tot een proefschrift kan leiden.

De Dienst Landbouwkundig Onderzoek en de Canadian Society of Soil Science boden me de gelegenheid me verder te verdiepen in het onderzoeksonderwerp tijdens een studiereis naar de VS en Canada. Verder hebben de Europese Gemeenschap (EG) en de Wetenschappelijke Raad voor het Regeringsbeleid financiële middelen verstrekt die onderdelen van het onderzoek mogelijk hebben gemaakt. Dr. M.H. Cornaert en Ir. J. Maes (CORINE-project, EG) ben ik bijzonder erkentelijk voor de kaarten van de EG die zij in digitale vorm beschikbaar hebben gesteld.

Bij de afwerking van het proefschrift was de ondersteuning van Liesbeth Ruyten en Bram ten Cate (afdeling Wetenschappelijke Informatie-overdracht), van Riet Meijnen en Wilma Nieuwenburg (afdeling Tekstverwerking) en van Martin Jansen, Hans Verwaal en Joop Ariese met hun medewerkers (afdeling Kartografie) onmisbaar. Karel Hulsteijn wil ik in het bijzonder bedanken voor het ontwerp van de omslag. Mijn dochter Tamara hielp me bij het ontwikkelen van de eerste ideeën hiervoor.

De uitgevers van de tijdschriften waarin een deel van de artikelen is gepubliceerd, bedank ik voor hun toestemming om deze artikelen voor dit proefschrift te mogen gebruiken.

Tot slot wil ik mijn ouders bedanken voor hun steun en de mogelijkheid die zij mij hebben geboden om te gaan studeren. Aan mijn voormalige RID/RIVM collega Bert-Jan Heij en de vele vrijwilligers die ik als bestuurslid van het rooms-katholiek schoolbestuur in Zoetermeer en van het kerkbestuur van de parochie Indoornik heb ontmoet, ben ik grote dank verschuldigd voor de tijd die we konden besteden aan de discussie over onze geloofsovertuiging; het heeft mijn leven onmiskenbaar gevormd. Carla, Tamara, Xavier en Rowin wil ik danken voor de rust die ze mij hebben gegund en de tolerantie tijdens perioden van geestelijke afwezigheid, met name het laatste jaar, toen de drukte groot was.

ABSTRACT

Van Lanen, H.A.J., 1991. Qualitative and quantitative physical land evaluation: an operational approach. Doctoral thesis. Agricultural University Wageningen, the Netherlands, (xiv + 196 pp.). 59 Figures and 16 Tables. Dutch summary.

Physical land evaluation methods are crucial for evaluating potentials and constraints of land for intended land use. Physical resources, such as soil, climate, hydrology, and topography are evaluated. Different technical procedures are used for physical land evaluation ranging from simple methods based on expert knowledge to more complex methods based on simulation models. The expert knowledge is derived from farmers' experiences. The methods using expert knowledge provide broad descriptive answers regarding land qualities and suitability and, therefore, they are described as qualitative evaluation methods. Qualitative physical land evaluation methods are developed and applied to screen possibilities of Dutch land for injection of slurry from animal manure, and to assess the growth potential of sugar-beet in the European Communities. Quick answers are obtained if the knowledge is captured into expert models in a computer system and when they are linked to a geographical information system.

The more complex methods are based on computer models simulating transient soil-water flow and crop growth. These methods are described as quantitative because they produce specific expressions in quantitative terms, such as occurrence probabilities of soil-water deficits, average crop yields, and temporal variabilities of crop yields. Quantitative methods are elaborated and their abilities are illustrated with the assessment of growth potential of potatoes in the Netherlands, and of sugar-beet and wheat in the European Communities. The impact of some land use options on crop production is explored, such as set-aside of land. Quantitative evaluation yields more specific results than qualitative evaluation, but it is more time-consuming and requires more specific input data. Because of these higher demands, a mixed qualitative/quantitative evaluation approach is introduced. In this approach expert models are used to screen land for severe restrictions for a defined use, and, subsequently, simulation models are applied to the remaining potentially suited land. An analysis of required efforts for various evaluation approaches is presented.

Finally, a quantitative physical land evaluation is elaborated to assess the effects of soil management on soil structure degradation and regeneration on farm scale. The major role of the land characteristic "soil macrostructure" is described. Several soil-structure types resulting from different soil management systems are recognized in sandy loam and clay loam soils, and characterized quantitatively in soil-morphological and soil-physical terms. The data are used as input for a soil-water flow model to calculate water-associated land qualities for land units with different soil-structure types. Differences in land qualities are interpreted as effects of soil-structure change. The modifications of the soil-water flow model to account for bypass flow and internal catchment (subsurface infiltration) are described.

Additional index words: physical land evaluation, land qualities, simulation model, expert model, crop growth potential, slurry injection, soil map, soil structure, soil degradation, bypass flow, internal catchment, European Communities

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PART I

1 GENERAL INTRODUCTION

2 HISTORICAL PERSPECTIVE

1 GENERAL INTRODUCTION

Land evaluation is the process of assessing the suitability of land for a specified kind of land use. Possibilities for land use types such as high-input arable farming, extensive grazing by dairy cattle combined with nature conservation or timber production in short-rotation forestry can be explored. The principal purpose of land evaluation is to predict the potentials and constraints of land for changing use. This may involve the introduction of a fully new land use type or the introduction of a new management practice, such as minimum soil tillage instead of conventional tillage (Dent & Young, 1981). Currently, in large parts of the world, land use has to be adapted in response to social and ecological demands. In developing countries land productivity is likely to be increased because of the still growing demand for crop and livestock products by the increasing population. Moreover, possibilities for growing non-food crops for agro-industrial processing have to be investigated to increase employment and income in the rural areas of these countries (e.g. Alexandratos, 1988; Van Dusseldorp, 1990). Further expansion of agricultural land in these countries is expected to be restricted, and, where possibilities for expansion may prevail, impact of this expansion on vulnerable ecosystems must be investigated thoroughly. In the industrialized world the pressure on land is probably even higher, which leads to a decrease in the area of agricultural land. Agricultural land is still being converted into urban and industrial uses. Moreover, the high-input agricultural production systems in these countries cause surplus production of major commodities and a significant contribution to the degradation of natural resources in terms of erosion and pollution of air, soil, and water (e.g. Briggs & Wilson, 1987; De Wit et al., 1987). It is obvious that land use has to be adapted. A thorough analysis of potentials and constraints of land for land use alternatives is needed before rational decisions can be made. Land evaluation provides objective sets of data on potentials and constraints, which can contribute to decisions on a sustainable land use.

Land evaluation deals with two major aspects of land, viz. physical resources and socio-economic resources. The physical resources include soil, topography, hydrology, and climate, whereas the socio-economic resources comprise, for instance, availability of labour, capital, size and configuration of land holdings, land ownership, and infrastructure. The physical resources are relatively stable. On the other hand, the socio-economic resources are more time-dependent because they are affected by the social, economic and political settings. The distinctly different nature of both resources has resulted in a procedure with separate evaluations, i.e. physical evaluation and economic evaluation, which may be processed subsequently or parallelly in an integral land evaluation approach (Food, 1976; Dent and Young, 1981). Physical land evaluation aims at assessing land qualities or at the suitability for a specific land use type, as conditioned by biophysical parameters (adapted from Beek, 1978; Smit et al., 1984). In this thesis land evaluation is restricted to physical evaluation.

Different technical procedures can be used for physical land evaluation. These procedures range from expert knowledge based on farmers' experience to process-oriented simulation models based on generally applicable physical and biological laws, which are derived from extensive laboratory and field experiments (Bouma, 1989).

The general objective of this thesis is to contribute to the development of a further quantification of physical land evaluation for agricultural purposes. The general objective is worked out by: (1) elaborating the different technical procedures in the context of physical land evaluation, also showing how land characteristics and pedotransfer functions are used to assess land suitability; (2) analysing differences and possibilities of qualitative and quantitative procedures and their complementary use; (3) applying the different procedures to small-scale maps to explore some land use options in the Netherlands and the European Communities; and (4) elaborating and applying the quantitative procedure on farm scale to obtain quantitative data on the effect of soil-structure degradation or regeneration.

Thus, we hope that this thesis will contribute to a development which finally enables us to present a quantitative assessment of possibilities for alternative land uses, and impact of these changes.

Part I mainly contains historical backgrounds on the development of land evaluation (Chapter 2). The different technical procedures for physical land evaluation methods are explained in detail in a number of papers in Part II. Part II starts with papers on the use of expert knowledge, which can be explained as a simple technical procedure for physical land evaluation. This procedure provides a quick but broad suitability assessment. The results of the assessment are expressed as well suited, moderately suited, or unsuited for a defined use. Because of the descriptive nature of the results, this type of evaluation is indicated as qualitative physical land evaluation. In Chapter 3 qualitative land evaluation is applied to investigate the possibilities of injection of slurry from animal manure in the Netherlands. The reasoning process to arrive from land characteristics at a suitability assessment, which is integrated in a computer system, is explained. Although results of qualitative methods can be very important in a reconnaissance stage of looking for feasible solutions of land use, in following stages, when a limited number of solutions is left, more specific results are generally required, which can be provided by quantitative methods. In this context, quantitative physical land evaluation methods are based on computer models simulating, for instance, soil-water flow, crop growth, and nutrient requirements. These models provide a quantitative expression of land qualities, of suitability in terms of crop yield, and of inputs required to obtain these yields. In Chapter 4 qualitative and quantitative methods are compared especially at land-quality level. In Chapter 5, a similar comparison is worked out for the suitability assessment in terms of the crop growth potential for sugar-beet within the European Communities. As quantitative methods require more efforts than qualitative ones, in Chapters 6 and 7 a mixed qualitative/quantitative land evaluation procedure is introduced for a more efficient use of quantitative methods when specific results are needed. First, qualitative evaluation methods select land with obvious restrictions, so that quantitative methods can be applied to the remaining, potentially suited land only. In Chapter 6, emphasis is also laid on the process of using land characteristics and pedotransfer functions to obtain input data for the quantitative land evaluation procedures. In Chapters 8, 9, and 10 quantitative physical land evaluation methods are applied on farm scale to obtain land qualities allowing differences between soil macrostructure to be analysed quantitatively. The differences can be interpreted as the effects of soil management on soil-structure degradation and regeneration.

At the end of the thesis, in part III, the coherence between the papers elaborated in part II is presented. In Chapter 11 the differences between the land evaluation methods are dealt with. Furthermore, shortcomings of the methods are touched on and possible solutions are given. Finally, the possible link between the physical land evaluation methods and socio-economic aspects to arrive at an integrated evaluation is discussed.

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2 HISTORICAL PERSPECTIVE

2.1 INTRODUCTION

From the earliest times, people have performed land suitability assessments. They learnt by experience how to estimate what land will produce and how it has to be managed. Beek (1980) mentions the experiences of the Jewish people when Moses sent a few of them on a reconnaissance to the land of Canaan. They reported that they had found land flowing with milk and honey (Num. 13:17-27). Apparently they considered this land very suitable for the type of land use they had in mind: camel grazing on the semi-arid plains and date-growing in the oases. Probably, the first farmers who settled in the Netherlands have also conducted suitability assessments. For instance, the relics of the linearbandkeramik people in South Limburg from about 4000 BC show that settlements are not randomly distributed over the region, but that they were predominantly founded at the edge of a loess plateau in the vicinity of surface water (Bakels, 1978). Aspects such as availability of perennial surface water, suited soils either for annual field crops or for grazing livestock, flooding risk, availability of firewood, availability of building materials, and presence of bovine animals were likely to be evaluated by the linearbandkeramik people.

Although land evaluation as one of the bases for settlement on new land or for land taxation (e.g. Aymans et al., 1988) must have a long tradition, more generally applicable evaluation procedures were not formulated until the 20th century. The main reason for this relatively late start is that land evaluation could not develop before the introduction of the basic concepts in soil science: the soil fertility concept by Liebig in 1840 and especially the soil geography concept by Dokuchaiev in 1883 (Van Diepen et al., 1991). The soil fertility concept, which was further elaborated by Mitscherlich in 1909, offered the opportunity to relate the production potential of particular land units to several interacting factors, such as soil and plant factors. The soil geography concept allowed meaningful, reliable soil surveys, thereby introducing a way to present the areal distribution of land characteristics, which are the basis for predicting the production potential.

According to Beek (1980) land evaluation methods developed after it became clear that soil surveys needed to be interpreted before they could be understood by planners, engineers, extension officers and farmers. A strong development has occurred since the thirties, because then intensive soil survey programmes started in the United States of America. These programmes commenced as a response to a sudden uncontrolled intensification of both agricultural land use and settlement processes, which were expected to threaten the food production.

Several land evaluation concepts and analytical procedures have been developed since the thirties, which, depending on the purpose, were grouped in several ways (Stewart, 1968; Food, 1974, 1975a, 1976; Gibbons & Haans, 1976; Beek, 1978, 1980; Lee & Van der Plas, 1980; Dent & Young, 1981, McRae & Burnham, 1981; Feyen, 1981; Haans et al., 1984; Sys, 1985; Verheije, 1986; Beek et al., 1987; Lee, 1987; Bouma, 1989; Bouma & Bregt, 1989; Dumanski et al., 1989, Thomasson & Jones, 1989; Van Lanen & Bregt, 1989; Van Diepen et al., 1991). In order to show different procedures in physical land evaluation and the development in time, the evaluation approaches have been grouped in this thesis as follows:

- qualitative evaluation mainly based on expert judgement;
- qualitative evaluation based on parametric methods, and

- quantitative evaluation based on process-oriented simulation models.

Qualitative and quantitative physical land evaluations were distinguished from each other by their possibilities to express the output, such as crop yield or annual timber increment, in quantitative terms. The way of expressing the results is closely related to the underlying technical procedure. Other suitability criterion variables (Beek, 1978) or indices of performance (Smit et al., 1984) than crop yield can be identified indeed. In physical land evaluation, however, crop yield, as an integrator of many land aspects, has proved to be the most reliable estimate of comparative value of each land unit to be studied (Dumanski & Onofrei, 1989). A similar statement was made by Aandahl (1958) when he discussed the importance of land productivity as a collective term to include responses to all possible alternative ways of using and managing soils. Beek (1980) also states that yield predictions are an important criterion to group land for specific land use purposes.

The proposed grouping assumes a clear distinction between qualitative and quantitative physical land evaluation procedures. In practice, however, all kinds of intermediate ways occur. In this chapter only the major evaluation procedures are presented and for reasons of clarity, they are presented as if they solely belong to one group.

First, the above-mentioned groups are discussed in an international context followed by the most relevant developments in land evaluation in the Netherlands.

2.2 INTERNATIONAL SETTING OF LAND EVALUATION APPROACHES

2.2.1 *Qualitative physical land evaluation based on expert judgement*

Physical suitability obtained by qualitative procedures is presented in a categoric way, which means that a small number of discrete ranked suitability classes is allocated to land (e.g. McRae & Burnham, 1981). The content of the suitability classes is qualitatively described in terms of highly suitable, marginally suitable, currently not suitable and permanently not suitable. Van Diepen et al. (1991) use the term conventional, interpretive grouping of land for this type of ranking, whereas McRae & Burnham (1981) characterize them as categoric systems.

Two different types of evaluation methods belonging to this group can be recognized: the land capability classification and the land suitability evaluation according to FAO standards.

2.2.2.1 Land capability classification

Land capability refers to the potential of land for a number of predefined major land uses. It is not intended to give an assessment for a specific crop or a specific farm management practice to be selected by the land evaluator. Beek (1978) refers to land capability systems as general-purpose systems. There is a priority sequence of major land uses built into the capability system, assuming a descending sequence of desirability (Fig. 1). Usually the sequence horticultural crops, arable crops, pasture, woodland and recreation/wildlife is implicitly considered. Land with the highest capability, Class I land, is versatile. When the capability of land decreases, the land is suited for a decreasing number of major land uses. Land with the lowest capability can only be used for recreation/wildlife. The capability assessment refers both to crop growth conditions and to land management operations, such as soil conservation practices.

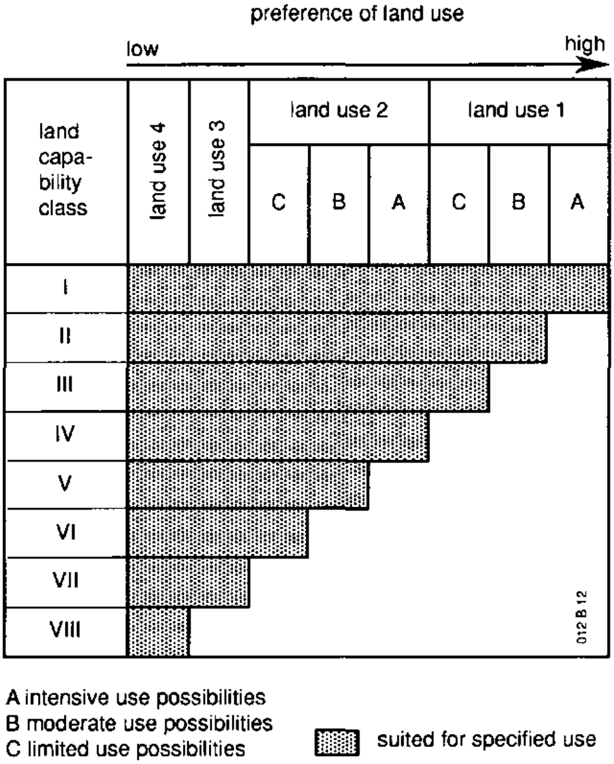

Fig. 1 General outline of a land capability classification system (adapted from McRae & Burnham, 1981).

The land capability approach uses the so-called limitation method, which implies comparing land characteristics of a land unit with critical limits of each capability class. The values of land characteristics are tested first against the limits of the highest capability class and, unless all the limits are met, the land unit automatically falls to the next lower class. This sieving process continues until a capability class is found at which all the limits are met. This means that if one limitation is of sufficient severity to lower the land unit to a lower class, it is allocated to that class, no matter how favourable the other land characteristics may be (law of minimum). The nature of the severest limitation, e.g. erosion, excess water or climatic limitation, is specified in the capability assessment. According to Dent & Young (1981) the capability classification follows no deep principles. Essentially, expert knowledge based on compiled farmers' experiences is related to land characteristics to obtain limits for the capability classes.

Land capability classification systems are the most widely used methods for evaluating agricultural land. Developing land capability classification started at the United Stated Department of Agriculture (USDA) in the thirties as part of the erosion control programme. Since the initiation, increasing attention has been given to other limitations than erosion (Klingebiel & Montgomery, 1961). The USDA system distinguishes eight capability classes ranging from I (best) to VIII (worst). Classes I-IV can be used for arable farming, whereas classes V-VIII cannot. The amount of possible arable crops progressively decreases and expenditure for conservation practices increases through classes I to IV. Classes V-VII show a decreasing capability for pasture, whereas class VIII cannot be used for any commercial plant production. Relatively broad descriptions of the classes are provided. The land evaluator has to carry out further refinement to adapt them to local conditions. This task requires much expert knowledge of the interaction between land characteristics and experience of local farmers. Hardly any socio-economic assumptions have been explicitly stated; one of the exceptions is the supposed 'moderately high level of management'.

The USDA capability classification system has been adopted in many other countries, industrialized as well as developing. In most cases, the number of classes, the limits to distinguish different classes, or the preferred sequence of major land uses were modified in order to be better accommodated to the prevailing conditions (McRae & Burnham, 1981). In some countries, extensive field programmes were carried out to investigate the limits for the suitability classes (e.g. Rowe et al., 1981; Dent & Young, 1981) Probably the best-known capability classification systems outside the United States are the systems applied in England and Wales, and in Scotland (Bibby & Mackney, 1969; Ministry, 1974).

Land capability classification was originally developed to support farm-planning at relatively large-sized farms. The capability map shows the farmer or extension officer which land of the farm can be used for which purpose and which conservation practices have to be carried out. Later on, the capability classification has been used for many other purposes, such as resource inventory to identify best agricultural land (McCormack, 1971) or to protect best agricultural land against urban development (Ministry, 1974), local government planning and environmental planning (Ministry, 1974), village land reorganization and new land settlement in developing countries (Dent & Young, 1981).

The main advantage of the land capability classification system is the versatile and simple basic structure of the system. It is simple to adapt the system without changing the basic structure. The results are easy to present and to understand. The principal disadvantage is the predefined preference for arable use, which does not allow land for other uses to be classified adequately. Planners responsible for livestock farming and foresters do not like being told that they have to look for their land in the lower capability classes. Other restrictions of the system are the lack of information on the suitability for specific crops with different agro-ecological requirements and the overestimation of the capability of land with many minor limitations. Furthermore, climatic limitations are not satisfactorily dealt with in the capability assessment. For instance in England and Wales, altitude and annual rainfall are the only land characteristics used. Although the effects of land improvements can be incorporated in the capability assessment, the system cannot properly assess the capability of the land for various potential situations, e.g. the effects of a global climate change. A comprehensive analysis of the advantages and disadvantages of the capability classification system has been given by Dent & Young (1981) and McRae & Burnham (1981).

Detailed descriptions of the land capability classification including guidelines for critical limits of the capability classes have been presented by Klingebiel & Montgomery (1961), Bibby & Mackney (1969), Dent & Young (1981), McRae & Burnham (1981), Rowe et al. (1981), and Sys (1985).

2.2.1.2 Land suitability evaluation according to FAO standards

Another qualitative physical land evaluation procedure that is mainly based on expert knowledge is the land suitability evaluation method developed by FAO (Food, 1976). Land suitability evaluation aims at assessing the suitability of land for a specified kind of land use. The land use type (LUT) has to be selected by the land evaluator and is not specified by the evaluation system itself. The suitability assessment has to be repeated for each LUT, relevant in an area, allowing the suitability to be compared over land units for the LUTs considered. A sequence of preferred land uses, as in the capability classification, is purposely not predefined. Beek (1978) indicates land suitability evaluation systems as specific-purpose systems.

Ideally, a suitability evaluation starts with a purpose-related identification of the relevant LUTs (Fig. 2). At first, the formulation of the LUTs can be relatively vague. Based on the LUTs, crop and management specific requirements (LURs) are defined; this implies characterizing what the land should offer. Furthermore, required inputs (such as labour, fertilizer) and expected outputs (such as crop yield, meat and timber productions) are described in this phase. Then, relevant land qualities (LQs) are selected, which are derived from a combination of land characteristics (LCs). LQs provide information on what the land units offer. In the suitability evaluation according to the FAO standards, land is not evaluated as a whole, but land is split up into LQs and LCs. In a matching procedure, LQs of each land unit are compared with the LURs in order to obtain an overall suitability assessment of the land unit for each of the LUTs considered. Besides an estimate of the production potential, the overall suitability includes an assessment of the environmental impact. This overall suitability has a provisional status, because the LUTs have to be investigated for required modifications. These modifications could include either adapted LURs or land improvements which, of course, increase costs of the intended land use change, but which improve one or more LQs. After modifying the LURs or the LQs, the next iteration step in the evaluation process is conducted. This leads to further refining LUTs, LURs, LQs, and overall suitabilities as the number of iterations increases. Finally, acceptable results are obtained, which include the final descriptions of the LUTs and the overall suitabilities of the land units for each of these LUTs. In practice, however, the LUTs are usually fully defined at the beginning of the land evaluation, which means that the complete evaluation procedure is carried out only once. In Chapters 3, 4 and 5, where qualitative physical land evaluation is applied, the latter procedure was followed. The suitability evaluation is preferably concluded with a field check of the estimated suitability. The results of the physical suitability assessment can be used in a socio-economic analysis. When the physical suitability assessment is the final product, the socio-economic information included in the LUTs is usually only broadly described.

The essence of land suitability evaluation is comparing LQs with the LURs of the various kinds of land use for which the land might be suited. A severity level of an LQ indicates the degree of limitation or, in case of no limitations, that the LURs are fulfilled. Characteristic descriptions of the severity levels are, for instance, no or slight limitations, severe limitations, or extreme limitations. Compared to the land capability classification there are no essential differences in the way the limits are set. Similar to the capability classification, land evaluators use expert knowledge based on farmers' expertise, supplied with field experience of relationships between LQs and farm outcome or the output of woodlots (e.g. Van Diepen et al., 1991). Therefore, the definition of class limits of LQs, which depend on the LURs associated with a LUT, can substantially benefit from the knowledge already obtained in land capability classification. The overall suitability, which is derived from the severity levels of the LQs, is usually based on the limitation method, although other methods are available (Dent & Young, 1981). This procedure takes the lowest individual severity level of the LQs considered as limiting to the overall suitability. Although LQs are used in the suitability evaluation instead of LCs, the essence of the suitability assessment is not principally different from that of the capability classification.

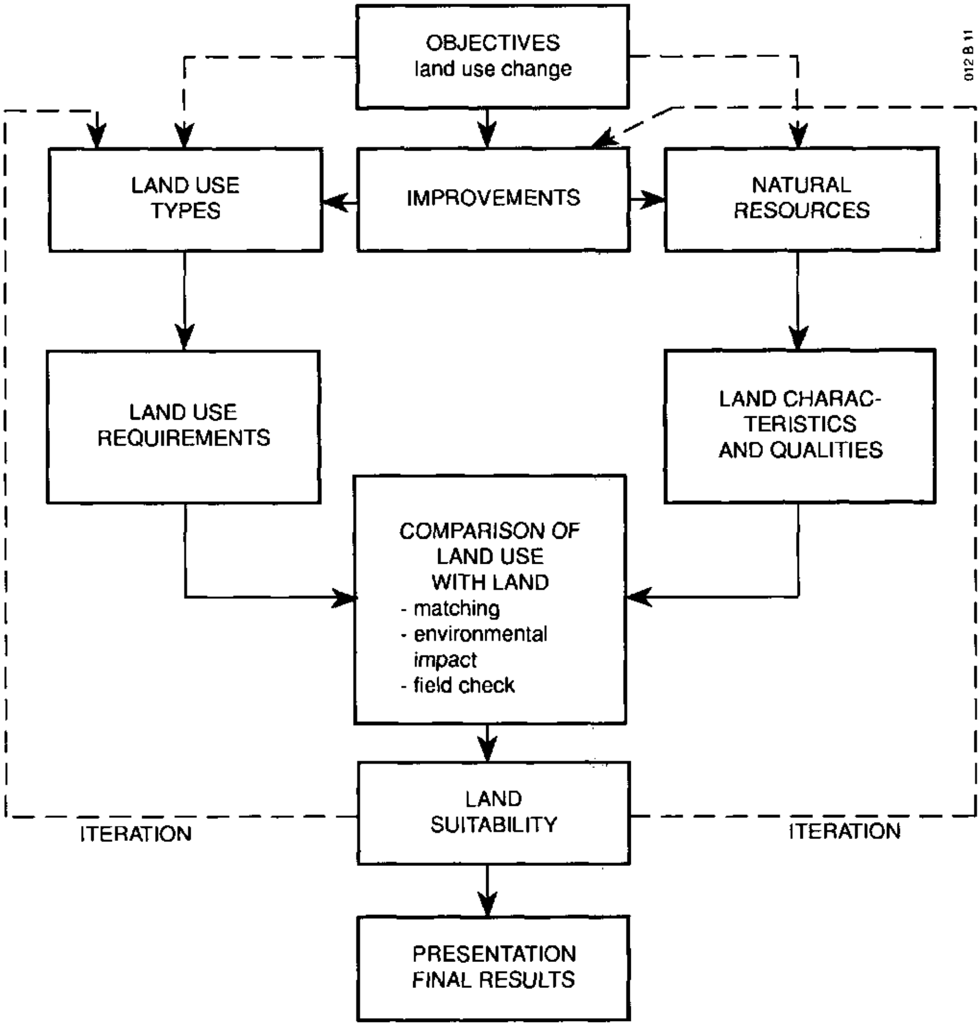

Fig. 2 General outline of the land suitability evaluation process (adapted from Dent & Young, 1981).

Land suitability evaluation probably has a long tradition. Procedures, however, have not been standardized earlier than the seventies. Then, FAO initiated a series of international discussions (Food, 1972, 1973, 1974, 1975b; Brinkman & Smyth, 1973; Beek, 1978), which eventually resulted in A Framework for Land Evaluation (Food, 1976). The foundation of the FAO framework was laid at an expert consultation in Wageningen in 1972, where a background document was discussed that had been prepared by the Dutch Small Committee for Land Evaluation and the FAO Inter-Divisional Committee on Land Appraisal (Brinkman & Smyth, 1973). The FAO framework itself does not contain an evaluation system, but it is a set of principles and concepts by which local, regional or national evaluation systems can be constructed. Six basic principles have been formulated: (1) suitability assessment is for a specific kind of land use; (2) benefits obtained need to be compared with inputs needed; (3) evaluation must have a multidisciplinary nature; (4) evaluation terms have to be relevant to the physical, economic and social context of an area; (5) sustainability is required, and (6) two or more kinds of land use have to be compared.

Overall suitability of land is expressed in two suitability orders: suitable land and not suitable land. The orders have been further subdivided into two or three classes. For suitable land (S) three classes have been distinguished; highly suitable land (S1), moderately suitable land (S2), and marginally suitable land (S3). Unsuitable land has been divided into land having limitations that might be surmountable (N1; currently not suitable), and land with limitations that cannot be improved (N2; permanently not suitable), because of, for instance, steep slopes or rock outcrops. Furthermore, the type of the major limitations can be provided except for class S1. A detailed description of the suitability classes has been given by FAO (Food, 1976), Dent & Young (1981), and McRae & Burnham (1981). In this thesis, the land suitability evaluation according to FAO is classified as a qualitative system because of the descriptive nature of the results, which are predominantly based on expert knowledge. With time, of course, expert knowledge was more and more fed by measurements on experimental fields and an increasing number of observations from surveys, which, however, were not translated into generally applicable physical and biological laws. Use of the gathered knowledge has been restricted to an increased reliability of the class limits of LQs and suitability classes.

In the late seventies and the early eighties, guidelines for land suitability evaluation based on the concepts of the FAO framework were elaborated for valleys in a tropical rain area (Veldkamp, 1979), rainfed agriculture (Food, 1984a), for forestry (Food, 1984b), for irrigated agriculture (Food, 1985), and for extensive grazing (Siderius, 1984).

Land suitability evaluation according to FAO standards has been applied in many parts of the world, especially in the developing countries. Beek (1978) and McRae & Burnham (1981) mention a number of applications. Despite the great number of evaluations, applications of the FAO framework taking into account all the proposed aspects are rare (Van Diepen et al., 1991). Usually only parts of the FAO framework are used. Even some major FAO projects (Food, 1978) concentrate on physical aspects of land only against a simple socio-economic background, as has been done in Chapters 3, 4, and 5 of this thesis. Moreover, FAO states that a selective use of its framework has proved to be useful in a wide range of circumstances (Purnell, 1984). Some elaborated applications of the FAO framework are the land evaluation studies for the Kisii area in Kenya (Wielemaker & Boxem, 1982) and for the Leziria Grande project in Portugal (Beek et al., 1980). In the latter project one of the principal objectives was to confirm the applicability of the FAO framework, although no clear conclusion on this part of the project has been published.

The applicability of land evaluation according to FAO standards has substantially increased by the introduction of computer technology in land evaluation during the eighties. Wood & Dent (1983) demonstrate the combined use of computer data bases and expert knowledge incorporated in a computer system to evaluate land suitability for a number of specific crops and tree species under tropical conditions. Similar evaluation systems for other crops and environments have been established by, for instance, Jones & Thomasson (1987), Batjes & Bouwman (1989), Hong Cheng (1989) and Robert (1989). All these evaluation systems contain knowledge on ratings for land qualities and overall suitabilities for specific crops in agro-climatic zones. Their transferability is limited because the expert knowledge only applies to the conditions for which the systems have been developed. A more versatile system to evaluate land according to the FAO standards is the Automated Land Evaluation System (ALES) introduced by Rossiter (1990). This system does not contain any knowledge by itself, but it offers the opportunity to capture it quickly. Moreover, facilities are provided to link the system to geographical information systems. Expert models built with ALES are dealt with in the Chapters 3, 5, and 6.

Although the above-mentioned evaluation systems are automated, they are still indicated as qualitative systems in this thesis because of the use of expert knowledge and the descriptive nature of the results. It should be noted, however, that this characterization is not in accordance with the opinion of some of the developers (e.g. Wood & Dent, 1983) or others (e.g. Beek et al., 1987).

During the seventies and eighties, at the University of Amsterdam (e.g. Vink, 1982; Tideman, 1984) and ITC (e.g. Zonneveld, 1984) a type of land evaluation evolved based on the principles of landscape ecology, which uses the term "land" as broad as it has been defined by FAO (Food, 1976). According to this approach, land includes all relevant horizontal and vertical interactions between living and non-living elements in the landscape, including human beings. A major example of the elaboration of this type of land evaluation is presented by Vos & Stortelder (1988) for the Solano Basin in Tuscany, Italy.

An advantage of the introduction of land suitability evaluation according to the FAO framework is the elaboration of the concept of land use and associated crop and management requirements. These requirements were formulated against a socio-economic setting as one of the driving forces in evaluation studies. Another advantage is the presentation of the suitability in terms of alternatives for land use, which is a more useful format than capability classification for making decisions by planning and management authorities (e.g. Dent & Young, 1981). Although the principles of land suitability evaluation are straightforward, application is complex. As the concepts and guidelines have to be worked out for every type of application, the qualifications of the applicability of the FAO framework differ. Van Diepen et al. (1991) give some comments and also review remarks made by others. Especially the concept of the land quality and its functionality related to the land use requirement to be formulated drew attention in the past (e.g. Radcliffe, 1983; Van Diepen, 1983; Brinkman, 1989; Rossiter et al., 1988).

Detailed descriptions of the land suitability evaluation system are presented by FAO (Food, 1976), Beek (1978), Dent & Young (1981) and Sys (1985).

2.2.2 *Qualitative physical land evaluation based on parametric methods*

2.2.2.1 Introduction

Parametric procedures usually allocate numerical ratings to separate land characteristics or land qualities depending on their relevance to the land use considered. Next, they are combined into one numerical result using a mathematical equation.

Only some of the parametric procedures present land productivity as output of the evaluation, either as a relative figure (expressed as a dimensionless ratio or a percentage), thereby expressing the productivity relative to a potential level, or as an absolute yield figure in kg ha^{-1} yr^{-1}. The majority of the parametric procedures render a relative figure which cannot be related to a yield level. Therefore, according to the criterion used in this thesis, the group of parametric procedures belongs to the qualitative physical land evaluation methods, elsewhere indicated as descriptive numerical classifications (Pons, 1975). Contrary to the classification proposed by Van Diepen et al. (1991), the numeric result is not sufficient to be called quantitative.

As parametric procedures are not further used in this thesis, they are only discussed briefly.

Parametric methods assess the suitability of land on a continuous scale, instead of discrete classes used in the land capability classification and the land suitability evaluation. The essence of parametric methods is a mathematical equation which can be expressed in the following ways:

Multiplicative, e.g. $P = A * B * C$
Additive, e.g. $P = A + B + C$

where P is the parametric score or index, and A, B, and C are the ratings of land qualities or land characteristics. An ideal combination of qualities or characteristics, representing the best land, would be expected to receive the maximum score and an index with progressively lower scores would represent less suitable land.

2.2.2.2 Multiplicative parametric method

The best-known multiplicative procedure to evaluate land is the Storie Index Rating (SIR), which was developed in the thirties in the USA (Storie, 1933) and which has been adapted many times afterwards and modified for other parts of the world. The equation to obtain the SIR (Storie, 1944) is written as:

$$\mathrm{SIR} = A * B * C * X$$

where: A is the rating of the nature of the soil profile, B is the rating of the surface soil texture, C is the rating of the slope, and X includes miscellaneous factors that can be modified by management, such as drainage, nutrient level, and erosion. The SIR is computed by assigning a fraction (McRae & Burnham, 1981) to each of the variables in the right part of the equation and then these variables are multiplied. Finally, the outcome is multiplied by 100 to obtain the SIR as a percentage. Principally the procedure to calculate the SIR is a qualitative physical land evaluation method as long as the SIR figures are not related to productivity data. A calibration procedure is required to find the relationship between the SIR and yields. When this calibration has been successfully conducted, the SIR is usually replaced by the Crop Productivity Rating (Storie, 1950) or the Index of Soil Productivity (Riquier, 1974). The soil potential rating proposed by McCormack (1987) follows a similar procedure.

Multiplicative parametric methods have been extensively used and compared with other methods of land evaluation by Sys and co-workers (Sys, 1985). Only a few of the methods developed by them can be indicated as quantitative procedures (e.g. Embrechts et al., 1989) because the results of all the other methods (land indices) do not express land productivity quantitatively. Thus, despite their numerical results, all these methods have to be classified as qualitative. Sometimes the results of the parametric procedures are only used to allocate land units to particular suitability classes, which have specified upper and lower limits for the index figures.

2.2.2.3 Additive parametric method

The German system of land evaluation (Bodenschätzung) is one of the best-known examples of an additive parametric method (e.g. Rothkegel, 1939; Herzog, 1954; Weiers & Reid, 1974; McRae & Burnham, 1981). For taxation purposes, an arable land index (Ackerzahl) and a pasture land index (Grünlandzahl) are estimated for each land unit on a detailed map scale. These indices are derived from land characteristics, such as soil texture, parent material, soil development stage, topography, climatic and soil-water conditions. Conversion tables are available (Oosting, 1942; Weiers & Reid, 1974; Albers et al., 1975) to assess these indices. The indices provide a relative suitability, related to a national standard of 100, which was awarded to land of a specified farm. The relative suitability is claimed to correlate well with crop yields. Thus, in spite of subjective criteria such as soil development stage, the German system actually is a quantitative evaluation system according to the definition used in this thesis. The indices are adjusted for less optimal conditions, e.g. risk of hailstorms, pests and weeds.

Other well-known and widely applied parametric procedures to predict the productivity are statistical models, such as poly-factor analysis and regression equations. The equations used have a somewhat other form than the above-mentioned parametric procedures. A characteristic form of a regression equation is:

$$Y = \mathrm{a}X_1 + \mathrm{b}X_2 + \mathrm{c}X_3 + \ldots\ldots + \mathrm{n}X_\mathrm{n}$$

where Y is the yield, and X_1 to X_n are land qualities or land characteristics, such as clay content, rainfall or temperature in a particular period. The regression constants a, b and c apply to the conditions and the purpose for which the regression was carried out. It is beyond the scope of this thesis to discuss the various parametric methods based on statistical models; for a review the reader is referred to McRae & Burnham (1981).

Parametric methods for land evaluation are simple, easy to apply and the subjectivity is reduced as compared to land capability classification or land suitability evaluation. Moreover, the combined effect of a number of small limitations of land characteristics is explicitly incorporated in the assessment. The continuous scale turned out to be useful for taxation purposes. The results of parametric procedures allow average figures to be computed over any area, e.g. farm and region. Though these aspects seem advantageous, many of them also have adverse points. Pons (1975) and McRae & Burnham (1981) comment on some of the apparent advantages. A weak point of the parametric methods is that the outcome does not provide any information on the nature of the limitations, which hampers checking the results. Furthermore, the numerical output of many parametric methods wrongly suggests the information to be quantitative. One of the major disadvantages, however, is the restricted possibility to cope with potential conditions. Extrapolations for any other conditions than those for which the equation was determined should be done with restraint. Introducing additional land characteristics or a suitability assessment for another crop requires a full recalibration of the parameters in the equation. This disadvantage is the main reason why parametric methods are not considered in the further development of physical land evaluation in this thesis.

2.2.3 *Quantitative physical land evaluation based on process-oriented simulation models*

The need for physical land evaluation procedures yielding quantitative assessments of inputs and outputs was postulated decades ago (e.g. Visser 1950; Vink, 1960; Stewart, 1968). Until the seventies only some parametric evaluation methods could provide quantitative output. All the other procedures allocated inputs and outputs to suitability classes, which were derived from independent sources, such as field experiments, inquiries among the farmers, and literature.

In the late seventies, the introduction of computer technology to the broad scientific community allowed simulation models to be developed and applied. These computer models simulate processes, such as water flow and crop growth, that are required for a quantitative assessment of physical suitability. More than 20 years ago, Nix (1968) foresaw this development using the crop growth theory developed by De Wit (1965). Nix already stated that as more comprehensive models of whole crop ecosystems could be developed and key parameters could be identified, it would become feasible, in concept, to predict the performance of a stated crop genotype at any location, given specified data on land characteristics and a historical record of weather data. Beek (1978) expected that the use of simulation models for specific land use processes showed great promise, but for the immediate future he foresaw that the application of the models simulating the performance of a land use system would probably remain too complex to entirely satisfy practical land evaluation.

In the late seventies computer models became operational for physical land evaluation purposes. Laws on physical and biological processes were represented and simulation of transient performance of the soil-crop system under a wide range of site conditions was possible. These laws are generally applicable and therefore, process-oriented simulation models principally have a higher transferability than evaluation systems mentioned in the above sections. A higher transferability is extremely essential, because potentials and constraints of land for various land use options can then be evaluated better.

The possibilities of applying transient process-oriented simulation models in physical land evaluation have received much attention during the last decade (e.g. Bouma et al., 1980; Bouma, 1984a, 1981, 1989; Driessen, 1986; Beek et al., 1987; Van Keulen et al., 1987; Burrough, 1989; Bouma & Bregt, 1989; Dumanski & Onofrei, 1989; Ritchie & Crum, 1989; Van Diepen et al., 1989; Feddes & Van Wijk, 1990). Some of the developments are briefly described in this section. In Chapters 4 up to 11 inclusive the potential of simulation models in physical land evaluation is comprehensively shown. The transient process-oriented simulation models used can be classified as deterministic models, which are more or less mechanistic (Addiscott & Wagenet, 1985).

Mechanistic implies that the model takes into account the most fundamental mechanisms of the processes, as presently known and understood. The deterministic nature involves that a system is assumed to behave in such a way that the occurrence of a given set of events leads to a uniquely-definable outcome. The models are not exclusively used for the overall suitability assessment, but they are increasingly applied to determine quantitative expressions for land qualities as the final result of the physical assessment.

To simulate soil-water flow, simple and comprehensive models were developed. For instance Neuman et al. (1975), Feddes et al. (1978, 1988), and De Laat (1980) developed some of these models. Feyen (1987) reviewed some of them. Soil-water models are essential because they provide quantitative information on important land qualities, such as the availability of soil water and oxygen in the root zone for crops. Thus, they integrate a number of land characteristics related to climate, soil, and hydrology. For example Bouma et al. (1980), Bouma (1986), and Bannink et al. (1988) showed how the soil-moisture supply capacity on a regional scale can be assessed by a simple soil-water model and by soil survey data. Furthermore, the soil-water models provide crucial information on land qualities associated with farm management, such as trafficability, workability, and harvestability. Buitendijk (1985), Wösten & Bouma (1985), Van Wijk & Feddes (1986), and Van Wijk et al. (1988) developed a pragmatic approach to obtain terms for these land qualities with soil-water flow models.

The water-associated land qualities can be incorporated into crop growth models to obtain a physical suitability assessment. After adaption, simple crop growth models (e.g. Feddes et al., 1978; Feyen & Van Aelst, 1983; Feyen, 1987; Van Lanen et al., 1987) can be applied in the context of physical land evaluation. Originally, these models were developed for water management purposes. More comprehensive crop growth models (e.g. Van Keulen & Wolf, 1986; Jones & O'Toole, 1987; Van Diepen et al., 1989) were used as well.

In the late seventies and the early eighties first attempts were made to use quantitative land evaluation procedures in land evaluation projects on small map scales. They were usually combined with qualitative procedures in order to cope with suitability criteria that could not be quantified. A well-known example is the Agro-Ecological Zones (AEZ) Project carried out by FAO (Food, 1978). In this project the area of the developing world suited for growing eleven major crops under rainfed conditions was determined by analysing thermal regimes to obtain a first major climatic subdivision. A further subdivision was obtained by applying a simple transient agro-climatological balance model, which evaluates precipitation, potential evapotranspiration, and average temperature. This model renders a length of the growing period, meaning the period that sufficient moisture is available for plant growth and the temperature is adequate. Then a major activity in the AEZ project, which involved computing constraint-free yields of the major crops for the different lengths of growing periods in the main climatic divisions, was carried out. The assessment of the economically useful constraint-free yield is based on generally applicable biological laws, which include computation of gross biomass production as a result of photosynthesis, respiration losses, and the harvest index. Eventually, a qualitative evaluation procedure was applied to correct the constraint-free yield for non-optimal conditions, such as weeds, pests, rainfall variability, and shallow soil depth.

In Canada the AEZ procedure with modifications for available data was adopted in the early eighties to obtain the national crop production potential for spring wheat, maize, soya bean, potatoes, and Phaseolus beans (Stewart, 1981; Dumanski et al., 1987; Dumanski et al., 1989).

Anticipated yield data, representing the yield potential under ideal management, have been determined by reducing the constraint-free yield for effects of soil-moisture stress, autumn workability probability, and unfavourable soil conditions.

2.3 DEVELOPING OF LAND EVALUATION METHODS FOR APPLICATION IN THE NETHERLANDS

2.3.1 *Introduction*

The physical land evaluation methods developed in the Netherlands are described in the following section. The description is restricted to those methods that have been developed for application in the Netherlands. The major Dutch contributions to some international developments were dealt with in the previous section. As most land evaluation methods for application in the Netherlands have been developed by the Soil Survey Institute (STIBOKA, now incorporated in The Winand Staring Centre) and the Agricultural University in Wageningen, the description focuses on these organizations.

In the Netherlands soil survey and land evaluation research have always been associated. The first research attempts at land evaluation were probably made in the thirties, when the Agricultural University in Wageningen carried out explanatory research on soil survey. Before World War II, Oosting (1939) already showed that the poor performance of some orchards could be explained by wet and slowly permeable layers in the subsoil. Oosting's evaluation results received criticism in these years. Edelman (1953) found that in these days national agricultural policy did not give priority to improving unfavourable soil conditions. The type of research initiated by Oosting and further elaborated by Edelman and his students formed the basis of the first land evaluation research by the end of World War II.

According to Haans (1979) the period 1945-1980 can be subdivided into three periods. These three periods and the period after 1980 are dealt with in the following.

2.3.2 *Period 1945-1955*

A characteristic approach in the period 1945-1955 was the use of crop performance as an indicator of soil behaviour (e.g. Edelman, 1953). As differences in crop response can also be caused by farm management, an important research activity was to separate this from differences solely induced by soil conditions. Van Liere (1948) developed the 'best-farm method' for this purpose, and De Bakker (1950) elaborated the 'poor-site method'. In their investigations, various mapping units were ranked according to crop performance, which was usually restricted to the yield of particular crops with known management practices over a number of years. Similar research for field-vegetable crops and soft fruit was conducted by Haans (1948) and for flower bulbs by Van der Meer (1952). Data on crop performance were gathered by analysing records of farmers, commercial institutions and research organizations. Furthermore, farmers' opinions on the relative merits of different soil types for various crops were another important source of information. The adopted evaluation approach required a close cooperation between soil surveyors and crop and farm experts to judge the farm management level. When the relationship between soil mapping units and crop response of a particular crop or group of crops had been established in the traditional centres, cultivation suitability assessments could be made outside these areas. This evaluation procedure was carried out to show that in certain regions the best land was not used for horticulture.

Use of the best land was found to be necessary because of economic reasons (Edelman, 1948). Moreover evaluations were conducted to develop horticultural settlement schemes and to convince town planners that some land close to a city had to be preserved for agricultural use instead of urban use because of its excellent suitability for horticulture (Edelman, 1953).

The demand for agricultural suitability assessments other than for horticulture was still low in those years. These assessments were expected to be of no use for land use planning, because the entire rural area with more or less suitable soils was already used. According to Edelman (1953), some found that only in the fringe of some forests might exist small expansion possibilities. But land suitability assessment for non-agricultural purposes was carried out. For instance, Bijhouwer (1948) showed how a soil map had been used for the town-planning of Schiedam.

2.3.3 *Period 1955-1965*

Land evaluation in the period 1955-1965 could benefit from the availability of the first nationwide soil map of the Netherlands. The map on a scale of 1 : 200 000 was completed in 1961. Moreover, after the International Soil Science Congress held in Amsterdam in 1950, the Dutch soil surveyors had much better access to the already long-standing experiences on land evaluation in the USA. In those years, land evaluation was indicated as 'land classification', which had been defined by Vink (1960) as 'all those groupings of soils that are made from the point of view of the people that are using the soil in a practical sense'. In the Netherlands use of the term land evaluation was avoided, because this was claimed by agricultural economists.

In this period a number of important soil surveys and associated land evaluations for different land use purposes in various parts of the Netherlands were conducted. Most of them have been published in the series 'Verslagen van Landbouwkundige Onderzoekingen'; Vink & Van Zuilen (1974) and Haans (1979) review some of these. Based on these experiences gathered from all over the country, Vink and his colleagues started to work out a common terminology and a methodology for the Netherlands. They defined soil suitability as 'the degree of success with which a crop or range of crops can regularly be grown on a certain soil within the existing type of farming, under good management and under good conditions of parcellation and accessibility' (Vink, 1963; Vink & Van Zuilen, 1974). Besides the yield expectation and its temporal variability, costs and efforts to obtain these yields were implicitly included in the definition. Furthermore, the assessment was set against the background of the technical and economic boundary conditions of that moment. A major land evaluation result from the period 1955-1965 is the nationwide map, scale 1 : 200 000, showing the suitability of Dutch soils for arable land and grassland (Vink & Van Zuilen, 1974). The developed suitability system recognizes five major classes. Each class presents a suitability assessment for both arable land and grassland. For instance, major class G includes soils generally suited for grassland, but mostly poorly or not suited for arable land. Each of the major classes is subdivided into classes and sometimes subclasses indicating a decreasing suitability or a specific limitation. Yield levels for various crops are given for some suitability classes. Particular features of the USDA land capability classification system (Section 2.2.1) can clearly be recognized in the suitability system.

The suitability classification systems developed in the periods 1945-1955 and 1955-1965 are dominated by the use of expert knowledge based on farmers' experiences, common sense, statistical data, and relatively few field experiments. These qualitative physical land evaluation methods, which are also classified as empirical methods (Gibbons & Haans, 1976), have a holistic nature:

they indicate the 'net effect' of all the combined physical factors of a land unit. The reasoning process of how land characteristics of a land unit are rated and combined to reach the suitability assessment is not explicitly elaborated. This implies that the suitability classes usually provide no information on the limitation(s) of particular soils. Some of the disadvantages of the holistic approach were already identified at the International Soil Science Congress in Amsterdam. At this meeting Visser (1950) stated that a parametric method based on polyfactor analysis would be more interesting to use in the Netherlands.

The suitability assessment for arable land and grassland holds for the socio-economic setting of about 1960. It would have been necessary to adapt the suitability assessments for other circumstances. Vink and co-workers tried to overcome this disadvantage by including more farm economics in the suitability assessment. They intended to add a quantitative expression to the qualitative description of the suitability classes. Vink (1960) classified this type of land evaluation as quantitative land evaluation. On about 150 farms they analysed soil conditions, yields of small field trails on different soil types, prices, costs, gross and net returns. Vink (1960) presents some results of this research programme. The final results, however, were never officially published.

During the period 1955-1965 the IJsselmeerpolders Development Authority (RIJP) conducted a comprehensive physical land evaluation for the reclamation of new polders from the IJsselmeer (Smit & Wiggers, 1959). Their evaluation was mainly based on two land characteristics, viz. percentage of soil particles less than 16 m and a parameter ('U value') representing the coarseness of the soil particles greater than 16 m. Land attributes, such as drought susceptibility, workability, and risk of wind erosion were derived from these characteristics in order to assess the physical suitability for broad types of land use. A general land use pattern for the polders was established based on the physical suitability assessments and the socio-economic setting of those days, implying that extensive areas of horticulture were unwanted, because of the threat of surplus production, and arable farming was preferred to dairy farming. Suitability assessments were also carried out by the RIJP for engineering purposes, such as for design of network of roads and canals, for soil drainage and for soil improvement.

2.3.4 *Period 1965-1980*

The disadvantages of the holistic nature of land evaluation systems that were developed before 1965 resulted in a growing need for causal and analytical research, which aims at a suitability assessment based on the ratings of limitations of individual land characteristics or qualities, instead of an overall direct rating of a soil type as such. Moreover, developments in technology and science resulted more and more in means to improve soils with limitations, and therefore people focused more on limitations than on yield differences between soils (Haans, 1979). Quantitative information on limitations was extremely useful for farmers or those who supported the land user, such as the extension service or the Government Service for Land and Water Use. Data on the overall suitabilities, however, were still required for land use planning. Furthermore, people needed suitability assessments for specific purposes instead of data on broad land use types.

In the period 1965-1980, a framework for soil survey interpretation (WIB-C) was developed to fulfil a number of these requirements. Applying WIB-C provides the user with data on specific aspects of soil performance allowing limitations to be identified. In addition, the reasoning process from soil data to interpretation result can be followed and the suitability is presented for a number of land use types, which are still relatively broad. The term 'land classification' used in the years before 1965 was replaced by 'soil survey interpretation', which was defined as 'assessments or predictions of the reactions or behaviour of soils under certain conditions, as a result of specific management, and assessment of suitability of the soil for a particular land use'. The term 'land' was replaced by 'soil' because of the broad concept of the former, which also included aspects such as accessibility and parcellation (Haans, 1984).

The Dutch WIB-C framework was developed along the same lines as the FAO framework (Section 2.2.1). It defines assessment factors, which are comparable to the FAO land qualities. The assessment factors are derived from land characteristics. The relevant assessment factors are combined into suitability classes using different conversion tables for each land use type. Conversion tables are available for arable farming, grassland farming (Table I), horticulture, and forestry. Assessment factors describe key aspects of soil behaviour, indicating the level of a specific process or site condition important for land use (Haans et al., 1984). Usually three or five levels are recognized. In Table II the assessment factors relevant to three major land uses types in the Netherlands are given. Not every assessment factor is relevant to each land use. For instance, the fertility status of the soil is only used for forestry; for arable land and grassland it is not significant because fertilizers are applied. The assessment factors are derived from land characteristics using substantially different methods in terms of degree of detail. For instance, a relatively comprehensive computation scheme is used to derive the moisture supply capacity from land characteristics, including precipitation deficit, soil texture of the topsoil,

TABLE I Conversion table to deduce the suitability for grassland from the assessment factors drainage status, moisture supply capacity and bearing capacity of the topsoil (Haans et al., 1984)

Drainage status	Moisture supply capacity	Bearing capacity		
		1[1]	2	3
1 or 2	1	1.1[2]	1.2	2.1
	2	1.3	1.4	2.1
	3	2.2	2.3	2.3
	4 or 5	3.2	3.2	3.2
3	1	1.1	1.2	3.1
	2	1.3	1.4	3.1
	3	2.2	2.3	3.1
	4 or 5	3.2	3.2	3.2
4	1	1.2	2.1	3.1
	2	1.3	2.1	3.1
	3	2.2	2.3	3.1
	4 or 5	3.2	3.2	3.2
5	1, 2 or 3	2.1	2.1	3.1
	4 or 5	3.2	3.2	3.2

[1] severity level; from 1 to 5 severity of limitation increases; 1: no limitations, and 5: severe limitations (see Table III).

[2] suitability class and subclass; 1.1 means class 1 and subclass 1. Class 1: highly suited soils, class 2: moderately suited soils, and class 3: poorly suited. Subclass indicates type of limitation.

TABLE II Assessment factors and their use for various land use forms in the Netherlands (Haans et al., 1984)

Assessment factor	Land use		
	arable farming	grassland farming	forestry
drainage status	+[1]	+	+
moisture supply capacity	+	+	+
bearing capacity topsoil	+	+	-
workability	+	-	-
structural stability	+	-	-
fertility status	-	-	+
acidity	-	-	+

[1] + relevant; - not relevant

thickness of the topsoil, and water-table class, whereas for other assessment factors a straightforward relation with only one land characteristic is used. Forexample, the assessment factor drainage status is inferred from the mean highest water-table only (Table III). Levels of the assessment factors assessment factors are determined independently of the land use type. The relevance of an assessment factor to a particular land use taking into account the requirements of that land use, is implicitly expressed in the conversion table.

TABLE III Relevant land characteristics to obtain the severity level of the assessment factor drainage

Level	Mean highest water-table (cm below soil surface)
1 (well drained)	> 80
2 (moderately well drained)	40-80
3 (moderately drained)	25-40
4 (poorly drained)	15-40
5 (very poorly drained)	< 15

An extensive description of the Dutch framework for soil survey interpretation, its development, assumptions, and guidelines is given by Haans (1979; 1980; 1984), Gibbons & Haans (1976), and Haans et al. (1984). Applications of the framework to various purposes, such as rural development plans, town-structure plans for urban development, engineering applications, and recreational purposes are discussed by Haans & Westerveld (1970), Naarding et al. (1970); Westerveld & Van der Hurk (1973), and Davidson (1980). Especially, The Government Service for Land and Water Use (LD) required a soil survey and a physical land evaluation for almost every rural development project. The results were used for land use planning and engineering purposes.

The development of the Dutch framework for soil survey interpretation is based on common knowledge of soil and crop growth processes, and various experimental trials to obtain relations between land characteristics and assessment factors for a wide variety of conditions (e.g. Hoekstra & Van Wallenburg, 1967; Van Lynden, 1967, 1977; Van Dam, 1967, 1973; Van Dam & Van der Knaap, 1968; Waenink, 1974; De Smet, 1975, 1979; Van der Knaap, 1977; Wopereis, 1980; Van Dam et al., 1986). In spite of all these efforts, only a few assessment factors could be quantified, viz. soil-moisture supply capacity and bearing capacity. The expressions for the other assessment factors as well as the overall suitability are still qualitative by nature. For instance, suitability class 1.1 for grassland (Table I) is described as 'soils highly suited for grassland farming; with high gross yields, low grazing losses, and a good trafficability (very good soils, practically without limitations)' (Haans et al., 1984). So, the output is still descriptive. The WIB-C framework was extensively tested and calibrated by many soil surveyors, who acquired their knowledge from observations of crop performance and soil behaviour during the extensive field programme for the Dutch soil map 1 : 50 000. Herewith, the relative ranking of mapping units could be tested well.

As only a few factors can be assessed quantitatively, the WIB-C system is classified as a semi-quantitative land evaluation system (e.g. Bouma, 1989).

Although significant progress was made from 1965 to 1980, the Dutch framework for soil survey interpretation (WIB-C) still had its drawbacks. Suitability assessment was restricted to relatively broad land use types. There was a need to develop guidelines for specific crops. Furthermore, the assessment factors and the suitability should be quantified and the dynamic nature of these quantities should be expressed. The WIB-C system is predominantly based on expert knowledge from soil surveyors and field trials. More generally applicable knowledge of physical and biological processes need to be incorporated in the suitability assessment, which enables people to explore the feasibility of all kind of potential land use options and alternatives.

2.3.5 *Period after 1980*

In the early eighties the elaboration of the Dutch framework for soil survey interpretation (WIB-C) was finalized and the interpretation results of many applications were stored in a soil information system (Bregt & De Veer, 1985; Bregt et al., 1986; Burrough, 1986). The final version of WIB-C for agriculture and forestry has been described by Van Soesbergen et al. (1986) and Van Lynden et al. (1985). A refinement of the procedure to determine the assessment factor 'bearing capacity of the topsoil' has been published by Van Wallenburg & Vleeshouwer (1987). Van der Knaap & Wopereis (1987) present the guidelines for suitability assessment for horticulture and ornamental trees, and Van der Knaap & Van Dam (1989) give guidelines for sportsfields. A comparison of the suitability assessment according to WIB-C with growth of different tree species on various locations is discussed by Waenink & Van Lynden (1989), and the guidelines for forestry are presented by Waenink & Van Lynden (1988).

For two crops, viz. fodder maize and industrial potatoes, the WIB-C guidelines for arable farming are further worked out into crop-specific ones (Van Soesbergen et al., 1984; Hamming & Van Soesbergen, 1988).

Besides finalizing the WIB-C framework, another important development in land evaluation research in the eighties was the elaboration of quantitative physical land evaluation methods, and the linkage of these methods with qualitative ones. Transient, process-oriented simulation models together with methods to capture expert knowledge into computer systems were adapted and extensively used by the Netherlands Soil Survey Institute (now incorporated in The Winand

Staring Centre) and the Agricultural University Wageningen. These developments are the subject of this thesis and therefore they are thoroughly discussed in the following chapters.

In the Netherlands development of quantitative physical land evaluation methods after 1980 (e.g. Bouma et al., 1980; Bouma, 1989) took considerable advantage of progress in simulation modelling of soil-hydrological and crop growth processes by hydrologists and crop scientists. Simulation models as developed in these sciences, however, were not straightforwardly applied to land evaluation. In the eighties some distinct differences could be recognized between the application of these models to hydrological investigations and land evaluation studies. Initially, in hydrology the soil-water flow models were developed without special attention to field soils. Soil horizons were supposed to be rigid, isotropic porous media (e.g. Feddes et al., 1978; De Laat, 1980; Abrahamse et al., 1982; Van Drecht, 1983). For instance, in the first part of the decade occurrence of preferential flow through macropores in clay soils was not considered in evaluating effects of drainage on arable crop yield (e.g. Van Wijk et al., 1988). In land evaluation research, adapted simulation models already broadly accounted for flow through macropores in order to obtain a quantitative assessment of soil-water deficits or trafficability (Bouma & De Laat, 1981; Wösten & Bouma, 1985). These adapted models were extended versions of the models developed by the hydrologists. Model modifications were based on soil-morphological observations conducted in the field and the laboratory. These observations were combined with soil-physical measurements allowing field soils to be characterized better in these models (Bouma et al., 1982; Bouma, 1984b). In part II of this thesis, use of morphological features and soil-physical characteristics is further worked out to define more realistic input data for an adapted soil-water flow model (Chapters 8 and 10). Model modifications are dealt with as well (Chapter 9). In the mid-eighties hydrologists also started to adapted their rigid soil-water flow models to consider macropores caused by swelling and shrinkage (e.g. Bronswijk, 1988). Compared to the models earlier modified by land evaluators, hydrologists use a more fundamental approach.

Simple and complex simulation models, which were used for land evaluation purposes, are explained in Chapter 6. When applying a model we must realize that calibrating too simple a model, which does not adequately represent relevant processes in field soils, leads to incorporation of its shortcomings in the calibrated parameters. This could affect the reliability of the outcome of the simulation model when it is applied to potential circumstances.

Another distinct difference between hydrological investigations and land evaluation studies was the way how spatially referenced soil data were considered. Generally, in hydrological investigations a very limited number of selected profiles were taken into account (e.g. Van Boheemen & Reuling, 1984; Van Wijk et al., 1988). No means of extrapolating the simulation results to other soils were presented. Conversely, land evaluation is usually directed to an area approach, often comprising many land units. Examples of this approach are given in Chapters 3, 5, 6, and 7. Variability between mapping units is considered in these studies. Furthermore, in land evaluation the spatial variability within a mapping (e.g. De Gruijter & Marsman, 1985) is taken into account as well when sufficient basic data are available. In Chapters 8 and 10 the impact of some variability within a mapping unit on water-associated land qualities is dealt with. In these cases, which apply to farm scale, the variability is caused by differences in soil macrostructure, which are associated with soil management. Variability within soils with identical macrostructures is expected to be substantially lower than the variability of the whole mapping unit. Some variability among soils with the same macrostructure, however, will remain.

Furthermore, in the eighties it was found that the modified soil-water flow models incorporated into physical land evaluation methods fit better to some land data stored in the data bases than many of the original models developed by hydrologists. Especially, water-table class data (Van der Sluijs & De Gruijter, 1985) can be more efficiently used as lower-boundary condition by the former models. The water-table class data have been gathered during the nationwide soil survey. Hence they are available for the entire Netherlands. As nationwide availability does not apply to other hydrological data, it is very crucial to have a model using water-table class data as lower-boundary condition. The soil-water flow and crop growth model adapted by the Government Service of Land and Water Use (LD) also uses water-table classes as major input data (Werkgroep, 1987). The effects of drainage on crop yield based on this model are extensively applied in the establishment of rural development plans in the Netherlands. For every rural development plan, water-table class data are collected to allow the model to be applied with updated data. In Chapter 6 the LD method is described in more detail.

Additionally to the availability of simulation models, the application of physical land evaluation methods during the eighties could substantially benefit from the development of geographical information systems (GIS) and pedotransfer functions. Pedotransfer functions relate readily available land characteristics to other characteristics, which otherwise can only be determined by a time-consuming and therefore expensive analysis (e.g. Bouma & Van Lanen, 1986; Vereecken et al., 1989; Wösten et al., 1990). Use of GIS (Chapters 3, 5, 6, and 7) and pedotransfer functions (Chapter 6) in the context of the application of physical land evaluation is explained in this thesis as well.

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PART II

3 COMPUTER-CAPTURED EXPERT KNOWLEDGE TO EVALUATE POSSIBILITIES FOR INJECTION OF SLURRY FROM ANIMAL MANURE IN THE NETHERLANDS

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3 COMPUTER-CAPTURED EXPERT KNOWLEDGE TO EVALUATE POSSIBILITIES FOR INJECTION OF SLURRY FROM ANIMAL MANURE IN THE NETHERLANDS

Submitted for publication in Geoderma

Computer-Captured Expert Knowledge to Evaluate Possibilities for Injection of Slurry from Animal Manure in the Netherlands

H.A.J. VAN LANEN[1)] & F.A. WOPEREIS[1)]

[1)] *The Winand Staring Centre for Integrated Land, Soil and*
Water Research, P.O. Box 125, 6700 AC Wageningen
(the Netherlands)

ABSTRACT

Surface application of slurry from animal manure substantially contributes to acid deposition in the Netherlands because of volatilization of ammonia. A qualitative physical land evaluation procedure was used to explore the possibilities for slurry injection. Expert knowledge, characteristic for qualitative land evaluation methods, was captured into the Automated Land Evaluation System (ALES) and successfully linked to a geographical information system (GIS) in which a small-scale soil map was stored. Decision trees to assess the physical suitability for slurry injection were developed within ALES. Maps are presented showing the physical suitability of the individual soil units and of agro-statistical regions. The latter were obtained by aggregation. A table is provided with the relative area for each suitability class of the agro-statistical regions. In a number of major Dutch grassland regions less than 40% of the area turned out to be suited for slurry injection, which was judged by the Dutch government to be insufficient for successful incorporation of injection in environmental legislation. A combined use of small-scale soil maps, computer-captured expert knowledge and GIS proves to be very useful in exploring land use options in a reconnaissance stage. Quick results are obtained which reduce the number of possible land use options within a short time. Thus, efforts can be concentrated on promising land use options, probably requiring application of quantitative evaluation methods.

INTRODUCTION

The last 30 years livestock density has increased enormously in The Netherlands. Pig and poultry farming in the sandy regions were the main causes for this increase, although the number of cattle also rose by about 60%. Import of relatively inexpensive feed-concentrates primarily stimulated this development. Increase in livestock density resulted in an excessive animal manure production. Van Boheemen (1987) estimated a manure production of about 99 000 000 t/yr, which means that about 50 t is available for every hectare of Dutch agricultural land. Manure production has reached such a level that the application of minerals through manure exceeds the crops' nutrient uptake capacity (Van der Meer and Berendse, 1990). In many sandy areas animal manure already causes pollution of soil, groundwater, surface water, and air by leaching, surface run-off, and volatilization of nitrogen components. Various measures have already been imposed or are being considered by the Dutch government to reduce detrimental environmental effects. The feasibility of the intended measures has to be investigated, because protection and renewal of natural resources has to be combined with other objectives such as production of abundant quality food, long-term resiliency, and profitability of agricultural enterprises.

Adaptation of agricultural systems can only be effective when the agro-physical and agro-ecological properties and potentials of land are taken into account. The potentials of land, as far as they are affected by relative permanent land characteristics, can be evaluated by physical land evaluation. The technical approaches for physical land evaluation range in degree of detail from farmers' experience and expert judgement to integrated computer models simulating soil-water flow, nutrient uptake, associated crop growth, and environmental effects (e.g. Bouma, 1989; Van Lanen et al., 1989a; Van Diepen et al., 1991). Qualitative evaluation methods, using expert knowledge, are particularly attractive when quick results are required or when insufficient data are available for quantitative methods based on computer models. Results of qualitative methods are mainly descriptive by nature (e.g. well suited, marginally suited). They do not give probability distributions of crop yields, machinery work days or nitrate concentrations as might be provided by quantitative methods. However, in a reconnaissance stage, when a broad-brush approach is still acceptable, qualitative methods can be very efficient (e.g. Verheije, 1986; Lee, 1987; Van Lanen et al., 1989b).

Recently, development and application of qualitative land evaluation models has improved substantially by the possibility to capture expert knowledge in computer systems (Wood and Dent, 1983; Maes et al., 1987; Rossiter, 1990). Especially the Automated Land Evaluation System (ALES) developed by Rossiter (1990), offers possibilities for a wide range of applications. In the study reported here an expert model was developed within ALES which was linked to a geographical information system (GIS) to evaluate the potential of Dutch land for the injection of animal manure produced in the form of slurry. Conventional surface application of the slurry significantly contributes to acid deposition, because of volatilization of NH_3. Since 1987 Dutch legislation has required arable farmers to plough slurry into the soil at the latest on the next day after application. As this measure was not feasible for grassland, the possibility of slurry injection into soil was examined by the Dutch government. Because results were needed urgently, ALES was applied together with a small-scale soil map, which is stored in the GIS.

The objective of this contribution is (i) to explain the combined use of GIS and computer-captured expert knowledge in qualitative land evaluation, and (ii) to present results on the possibility of slurry injection expressing the potential of the methodology developed. The complete study on possibilities for slurry injection in The Netherlands is reported by Wopereis and Schuiling (1990).

SOILS AND LAND EVALUATION METHOD

Soil Map 1 : 250 000

The Soil Map of the Netherlands on a scale of 1 : 250 000 (Steur, 1985; Steur et al., 1986), was used to investigate the possibilities of slurry injection. About 265 soil mapping units have been distinguished, distributed over the map in 6500 polygons (average size of the map polygons is about 500 ha). The major subdivision of the units (main classes) is based upon the type of parent material, namely peat, sand, Holocene marine clay, Holocene fluviatile clay, Pleistocene or old clay, and loess, and on flint content when this is high. Some land characteristics (LCs) have been distinguished for all the soil mapping units, e.g. **groundwater depth class, presence of slopes, stones in the subsoil, old clay or boulder clay in the subsoil**, and **flooding risk.** Other LCs are only relevant to a particular parent material, e.g. **soil texture of the topsoil** (mineral soils), **presence of $CaCO_3$** (mineral soils), **thickness of the topsoil** (sandy soils), **texture of the subsoil** (clay soils), **peat species in the subsoil** (peat soils), **type of the topsoil** (peat soils). The number of LCs for each soil mapping unit varies between 22 and 26.

The Soil Map 1 : 250 000 recognizes "class LCs" only (Bouma and van Lanen, 1986), also referred to as discrete LCs (Rossiter, 1990). The LC **soil texture of the topsoil** is given in 4 or 5 classes, depending on parent material. For the clay soils four texture classes have been recognized based upon clay content. The classes range from sandy loam to clay. For the sandy soils the median of the sand fraction has been used as a diagnostic criterion. Five classes have been distinguished, from extremely fine to coarse. The LC **groundwater depth class** is also expressed in five classes, which range from very shallow to very deep. These classes have been defined by the mean highest water-table (MHW) and the mean lowest water-table (MLW). The LCs **soil texture** and **groundwater depth class** belong to the discrete, ordered (i.e. ordinal) type of land characteristics, which means that the underlying continuous scale (e.g. clay content, median, MHW) is divided into classes. Most other LCs of the small-scale map have no underlying continuous scale. The number of classes of these unordered LCs is determined by the various appearances, which may be very diverse. For instance, the LCs **presence of slopes**, **stones** and **flooding risk** have two classes, i.e. "present" and "absent", and the LC **subsoil of sandy soils** has three classes, i.e. "with podzol-B", "without podzol-B; no hydromorphic features" and "without podzol-B; with hydromorphic features".

Many soil units have compound LCs. To these units two or more texture or groundwater depth classes have been allocated. The occurrence probability of the individual homogeneous subunits, e.g. 30% subunit X_1 and 70% subunit X_2, is not provided. Physical suitability for these compound units is presented as a range, considering the LCs of the subunits.

Automated Land Evaluation System

The Automated Land Evaluation System (ALES), developed by Rossiter (1990), is a framework for evaluators to build their own expert system. ALES allows physical and economic suitabilities, in accordance with the FAO-Framework for Land Evaluation (Food, 1976), to be assessed with a computer. Both frameworks only explain how to evaluate land; they do not contain any knowledge or evaluation results like several other soil information systems do (e.g. Robert and Anderson, 1987). Absence of actual knowledge on land utilization types (LUTs) in ALES is a typical distinction from evaluation systems, such as JAMPLES (Batjes and Bouwman, 1989), LEIS (De la Rosa et al., 1990) and the comprehensive Land Evaluation Computer System (LECS), developed by Wood and Dent (1983). For example, LECS aims at evaluating land for a particular group of crops and timber species, mostly grown under tropical conditions. Crop requirements under those conditions are incorporated in LECS. When land has to be evaluated for other crops or conditions, using ALES is far more effective than applying LECS and similar systems.

Five steps can be distinguished when ALES is used for assessing the physical suitability (Fig. 1):

(1) defining land use types (LUTs). The LUT in our study concerned an intensively managed dairy-farming system including injection of slurry on grassland;

(2) formulating land use requirements (LURs) for each LUT. They describe the conditions of land which are necessary for successful and sustainable application of the LUT;

(3) selecting relevant land characteristics (LCs). They describe the natural resources relevant for the LUT being considered;

(4) defining land qualities (LQs) and deducing these from LCs using decision trees. Ratings, or severity levels of LQs are determined for each mapping unit, i.e. no, moderate, extreme limitations etc. They express the degree to which a LUR is met by what the land offers. A land mapping unit (LMU) comprises a number of delineations on a map which are relatively homogeneous in terms of soil, climate, topography, hydrology;

(5) combining LQs using a decision tree to infer relative physical suitability for each LMU. Relative physical suitability, expressed in terms of highly, moderately, marginally suited, serves to rank LMUs on an agro-physical or agro-ecological scale.

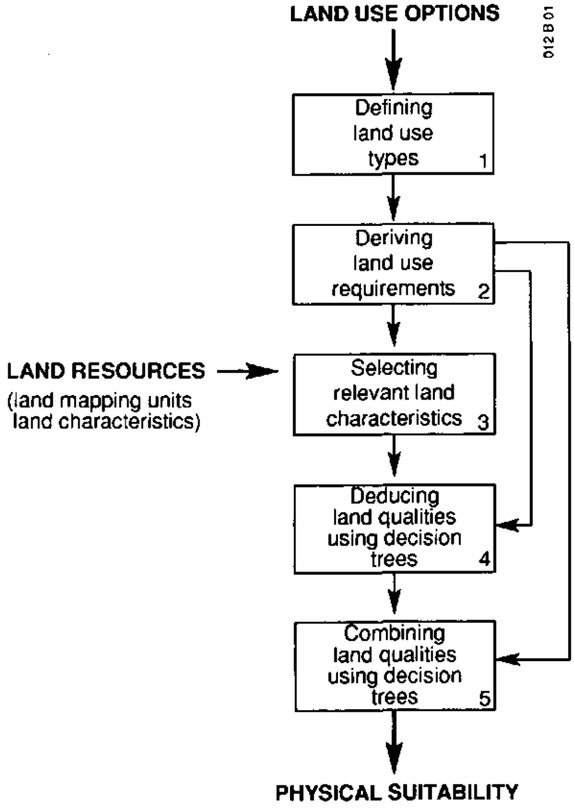

Fig. 1 Relational diagram for assessing the physical suitability using ALES.

In ALES the interrelations of LCs to define a certain LQ and of LQs to eventually arrive at the physical suitability assessment have to be accounted for in the form of decision trees. These trees are structured representations of a reasoning process needed to reach decisions. Decision rules are the key factors of the knowledge base to be built into ALES by the modeller. Actually ALES does not use LQs; the rating of the degree to which a LUR is met by what the land offers is straightforwardly derived from a combination of LCs (Rossiter et al., 1988).

In our study the knowledge-base system of ALES was used to compute the physical suitability only. We did not have to take advantage of ALES's ability to perform economic land evaluation.

Linkage to a GIS

Land evaluation models built with ALES do not have a spatial reference. Each LMU was evaluated independently of the geographical locations of the map polygons belonging to the unit. Geographical references of the LMUs polygons were needed because the eventual physical suitability for slurry injection had to be presented for the 14 so-called CBS/LEI regions, which are used for agricultural statistics in The Netherlands, and not for the individual LMUs only. CBS/LEI regions, also referred to as agro-statistical regions, are major areas of land that are relatively homogeneous in terms of agricultural use. They comprise, however, many soil map polygons belonging to different LMUs. Thus, in our study an LMU was a unique combination of a soil mapping and an agro-statistical mapping unit, usually distributed over various map delineations.

A partial linkage of ALES with a geographical information system (GIS) was necessary (Bulens et al., 1990) to enable computation of the suitability of CBS/LEI regions for slurry injection from the results of individual LMUs. The complete procedure has been schematically outlined in Figure 2. The GIS was used to make a map overlay of the relevant maps, i.e. soil and CBS/LEI regions, and to specify the LMUs in terms of map codes, areas and land characteristics. Data were stored into the ALES database. Subsequently the knowledge base was used to compute the suitability of each LMU. ALES results were then stored in the GIS database. ALES was able to import and export data and LMU definitions without re-keying. After storage in the GIS database, physical suitability of the LMUs was aggregated to determine the relative area of land occurring in the different suitability classes for each CBS/LEI region. Finally, maps and tables were produced using the GIS.

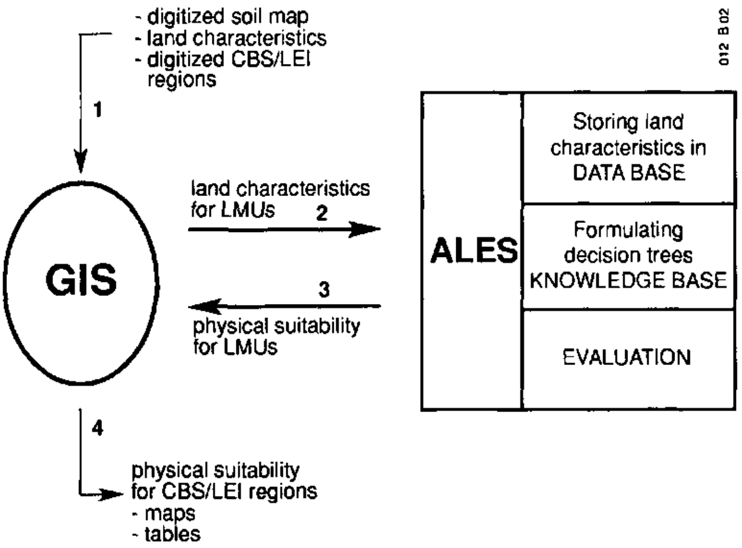

Fig. 2 General outline of partial linkage of GIS and qualitative physical land evaluation model. Figures indicate evaluation process sequence.

Land use type
Injection of slurry into grassland soils was considered for a LUT which comprises intensive grazing on intensively managed dairy farms (Wadman, 1988; Wopereis and Schuiling, 1990). Although the capital intensity was assumed to be high, the farmer did not own slurry injection equipment. Slurry injection was expected to be carried out by contractors. A heavy tank wagon with injection equipment was supposed to be used. A high tractive power is necessary because slurry is injected at about 15 cm to 20 cm depth and 50 cm apart. Grass sod damage by wheel slip has to be avoided. Slurry has to be applied in spring because most nutrients can then be taken up by the grass crop and losses due to leaching in autumn and winter are thus minimized (De la Lande Cremer, 1986). Therefore an adequate soil trafficability in spring is a prerequisite. Slurry injection can only be effective when the topsoil is sufficiently moist, because otherwise the injection slits may not close. Furthermore, obstacles in the subsoil might damage the injection equipment. Application of injection equipment will be hampered or even impossible on sloping land or on flooded land. Furthermore on sloping land lateral flow of slurry in the slits may occur, which leads to an unequal distribution.

Land characteristics and land qualities
The physical quality of the topsoil, which provides information on trafficability and possibilities for closure of the injection slits, was recognized as the dominant LQ for slurry injection (e.g. Soil, 1983). The rating of this LQ was derived from LCs such as parent material, soil texture of the topsoil, and groundwater depth class according to the decision tree presented in Figure 3. Five ratings were distinguished, expressing the physical quality of the topsoil in terms of no to very severe limitations for slurry injection. Furthermore the physical quality of the subsoil and general accessibility were identified as LQs. The physical quality of the subsoil was inferred from parent material, presence of old clay, boulder clay or a cemented podzol-B horizon. The subsoil starts below the A horizon or at 40 cm depth. Presence of old clay or boulder clay causes perched water-tables, which affect the trafficability negatively. Shallow, cemented podzol-B horizons might cause damage to the injection equipment. The LQ accessibility was deduced from the location of the LMU being on either sloping land or on land with a flooding risk. Two ratings were distinguished for the LQs physical quality of the subsoil and accessibility, i.e. no and very severe restrictions for slurry injection.

Physical suitability
The physical suitability was finally determined with decision rules based on a straightforward combination of the ratings of the three LQs (Table I). Five suitability classes were defined, e.g. from well suited to very poorly suited.

LMUs having a compound soil texture class or groundwater depth class were evaluated twice. In the first evaluation (evaluation A) the subunit with the finest soil texture or the shallowest groundwater depth class was assumed to be representative for the entire LMU. Thus, minimum possibilities for slurry injection were obtained, because these classes have the severest restrictions. In the second evaluation (evaluation B) the subunit with the coarsest soil texture or deepest groundwater depth class was used, thus overestimating the possibilities. In the case of a compound unit with three subunits, the subunit with the middle class was used in evaluation B. Eventually

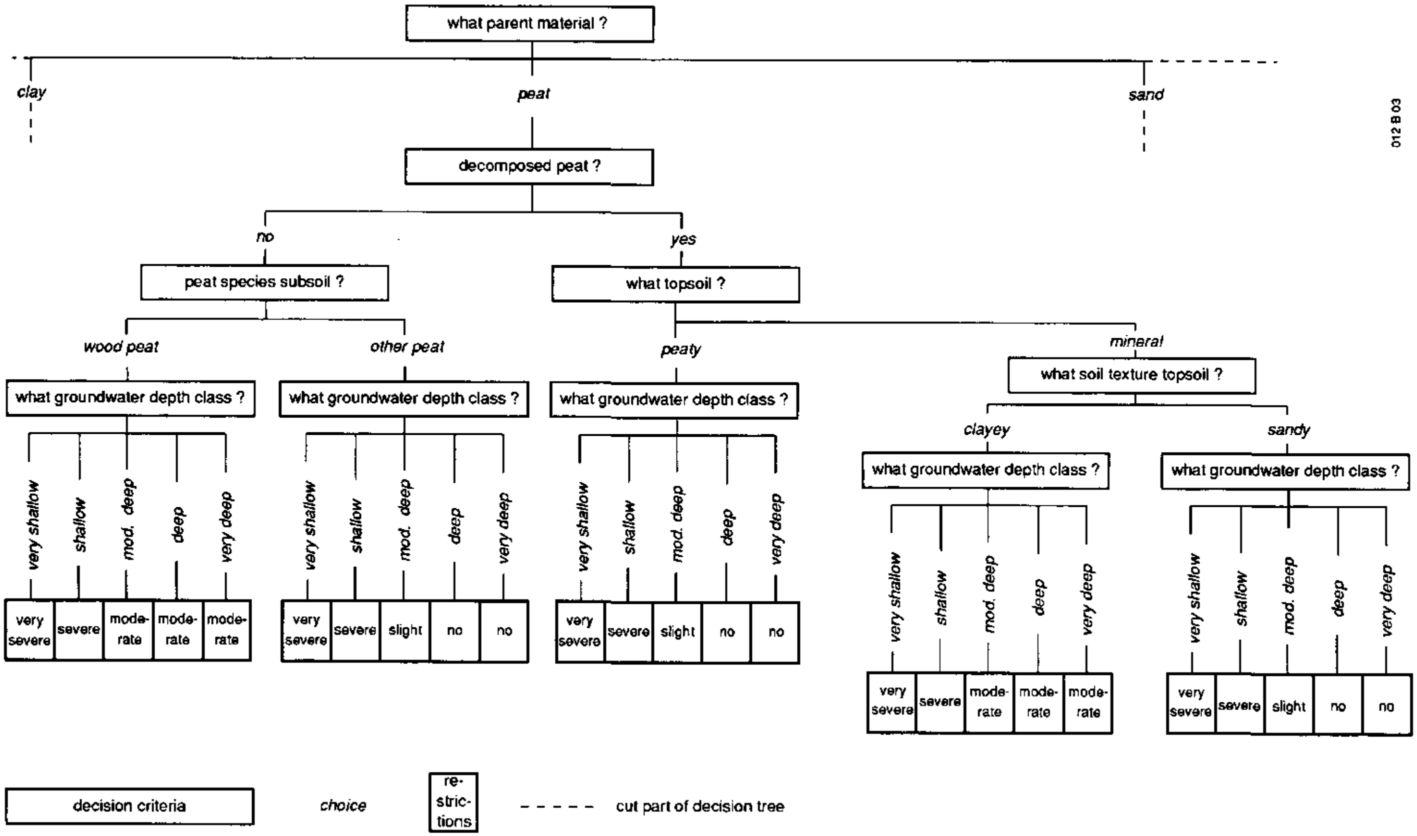

Fig. 3 Part of the decision tree to determine the LQ physical quality of the topsoil.

Table I Physical suitability assessment for slurry injection inferred from severity levels of the LQs accessibility and physical quality of both topsoil and subsoil.

Physical quality topsoil	Physical quality subsoil	Accessibility	
		no restriction	very severe restriction
no restriction	no restriction	1[1)]	4
	very severe restr.	1	5
slight restr.	no restrictions	2	4
	very severe restr.	2	5
moderate restr.	no restrictions	3	4
	very severe restr.	3	5
severe restr.	no restrictions	4	4
	very severe restr.	4	5
very severe restr.	no restriction	5	5
	very severe restr.	5	5

[1)] suitability; 1 to 5 are suitability classes for slurry injection:
1 = well suited, 2 = moderately well suited, 3 = moderately suited,
4 = poorly suited, and 5 = very poorly suited

for a compound LMU a range of physical suitabilities was presented when evaluations A and B did not render the same suitability class.

In the Netherlands climatic differences concerning precipitation and evapotranspiration are relatively small. The mean potential evapotranspiration (E_p) in the period relevant for slurry injection is small anyway ($E_p < 2$ mm/d) and differences in the mean monthly precipitation are less than 10 mm (Koninklijk, 1972). Therefore, climatic differences were not taken into account in the broad suitability assessment being considered here.

Large-scale injection of slurry is rather new, so that literature did not provide sufficient information. Therefore, we obtained expert knowledge by interviewing managers of experimental farms on different soils, experienced soil surveyors and farm mechanization experts. After implementing their knowledge in decision rules in a computer system, we asked the opinion of other soil surveyors and 20 grassland extension officers on a map showing tentative results. The decision rules were then adapted based upon their comments. Hardly any discussion existed among the experts on the (very) poor suitability of moderately poorly and poorly drained soils and fine-textured soils for slurry injection. The experts disagreed on the significance of possible damage to equipment caused by wood remnants in some peat soils, relevance of slopes in some regions, and the adverse effects of boulder clay deeper than 80 cm below soil surface.

The process of interviewing, implementing knowledge in decision trees, discussing the tentative suitability assessment, adapting the decision trees, and producing maps and tables took less than one month.

POSSIBILITIES FOR SLURRY INJECTION

The physical suitability for slurry injection of each LMU was determined with ALES and stored in the GIS. Two maps were drawn, showing the physical suitability of Dutch land for evaluations

A and B. A section of one of these maps is presented in Figure 4. The map shows evaluation B, which means an optimistic estimate for slurry injection possibilities. Boundaries and numbers of CBS/LEI are also presented. The Northern Grassland region (No. 3) is predominantly found to be poorly and very poorly suited. The major LMUs in this region are: (1) deep peat soils with a humic clayey topsoil (< 40 cm) and shallow to moderately deep groundwater depths, and (2) clay soils with more than 25% clay and a moderately shallow groundwater depth. In the Northern Sand region (No. 1) large sandy areas occur which are poorly suited, because of the presence of boulder clay in the subsoil. The Veenkoloniën region (No. 13) is a region with reclaimed cut-over raised bogs (De Bakker, 1979). In major parts of the Veenkoloniën well drained peat soils occur with a humic sandy topsoil (man-made) and sand within 120 cm. These soils are moderately well and well suited for slurry injection. With the exception of the eastern part,

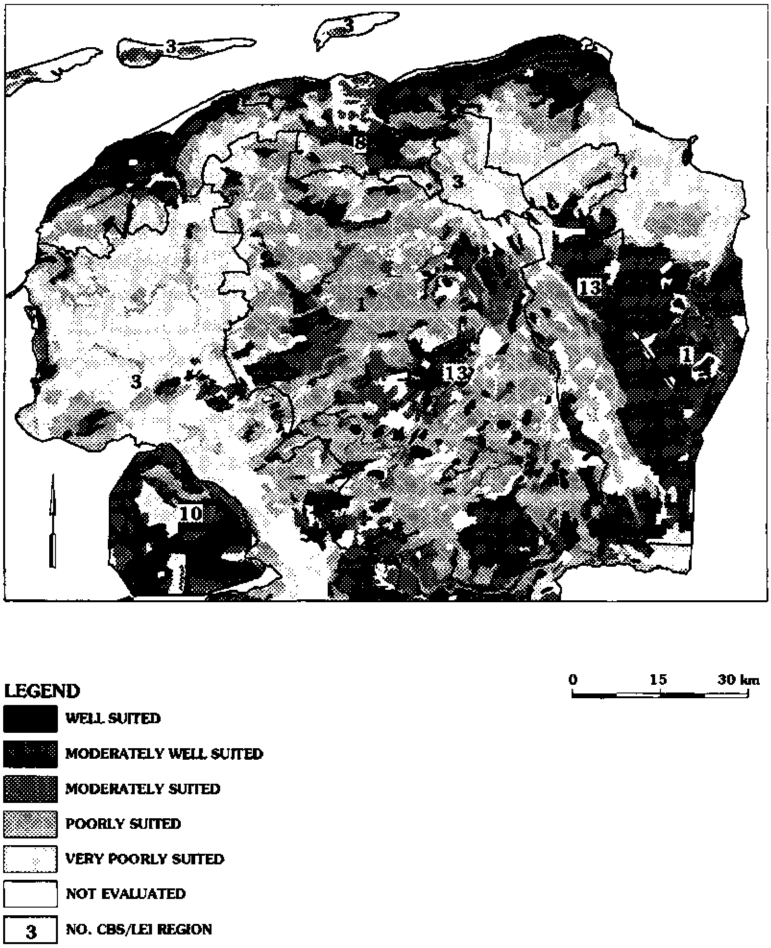

Fig. 4 Map section showing the physical suitability for slurry injection in the northern Netherlands (evaluation B)

the Northern Clay region (No. 8) is mainly found to be well suited. This region has well drained clay soils with a clay content usually lower than 25%. In the eastern part, soil drainage is less and the clay content is higher than 25%. Therefore, the suitability drops from well suited to poorly or very poorly suited.

The physical suitability of the LMUs was aggregated for the CBS/LEI regions. Subsequently, the relative area for each suitability class was computed for each region. The five suitability classes were combined into three main classes (I: moderately well and well suited, II: moderately suited, and III: poorly and very poorly suited). Figure 5 shows some results for the CBS/LEI regions, i.e. the relative area of class I land for injection of slurry throughout the Netherlands. Just like Figure 4 the map shows the results of the B evaluation described above. In the Northern Grassland region less than 40% of the evaluated rural land belongs to class I. The Northern Sand

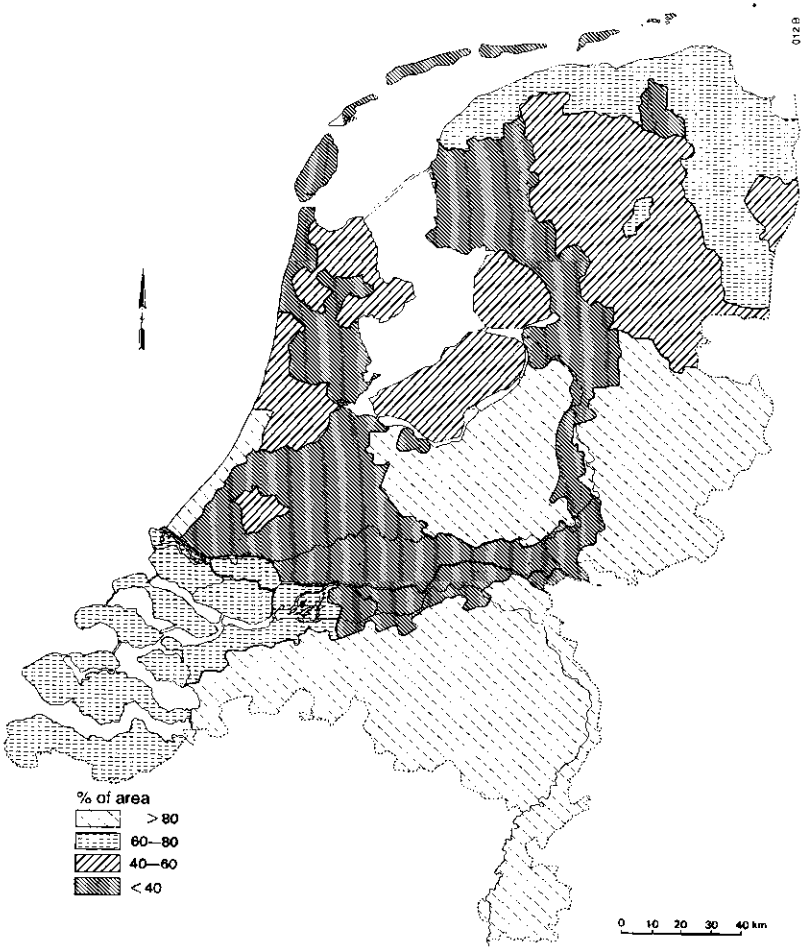

Fig. 5 Relative area (% of evaluated rural land) of class I land for slurry injection (evaluation B) within CBS/LEI regions.

region has between 40% and 60% class I land. The Veenkoloniën and Northern Clay regions have 60% to 80% class I land. More than 80% class I land can be found in the Central, Eastern and Southern Sand Regions. A comparison of Figures 4 and 5 shows that aggregation yields a far less detailed map, allowing an overview of the main results to be presented quickly. A disadvantage is the loss of information on the distribution of land within a CBS/LEI region belonging to a particular suitability class. For instance the distributions of class I land for the Veenkoloniën region and the Northern Clay region are completely different, as is shown by Figure 3. Still, in both regions 60% to 80% class I land occurs.

The relative areas for all the main suitability classes within the CBS/LEI regions for both evaluation procedures A and B are presented in Table II. The first six regions have more than 60 000 ha grassland each and were indicated as major grassland regions. As a whole, 41% to 60% of evaluated rural land is moderately well to well suited (class I) for slurry injection and 20% to 39% of rural land is poorly to very poorly suited (class III). The range is caused by the evaluation procedure for compound mapping units.

Table II Relative areas (% of evaluated rural area of the CBS/LEI region) for the main suitability classes for injection of slurry. Regions are ranked from high to low according to the relative importance of grassland.

CBS/LEI region	I[1]		II		III	
	A	B[2]	A	B	A	B
River Clay	19	26	45	68	37	7
Northern Grassland	15	35	8	16	76	49
Western Grassland	10	37	16	32	74	31
Northern Sand	29	48	12	12	59	41
Eastern Sand	52	84	23	6	25	11
Northern Clay	40	61	4	12	56	27
Southern Sand	65	83	18	8	17	9
Central Sand	43	82	36	16	22	3
Rest North Holland	27	56	43	23	30	21
Loess	79	81	4	11	17	8
Veenkoloniën	59	68	2	6	39	27
Rest South Holland	66	86	19	5	15	9
Holland and IJsselmeer Polders	36	47	39	39	25	15
Southwesterly Clay	68	72	25	25	8	3
Netherlands	41	60	20	20	39	20

[1] main class I combines suitability classes 1 and 2 (see Table I), II comprises class 3 and III combines 4 and 5

[2] A and B refer to the procedure for compound mapping units (see text)

Further use of the physical suitability results focused on class I land, because feasibility of slurry injection on class I land is beyond doubt. On class II and III land, on the other hand, farmers cannot be imposed to apply the injection technique. In major grassland regions, such as the Western Grassland, Northern Grassland, and River Clay regions, the relative area of class I land varies between 10% and 37%, 15% and 35%, and 19% and 26%, respectively. This indicates that there are small possibilities for slurry injection. In the Northern Sand region possibilities for injection are somewhat better, i.e. between 29% and 48%. The circumstances are even more favourable in the other two sand regions with substantial areas of grassland. In the Eastern and Southern Sand regions, the relative area of class I land ranges from 52% to 84%.

The differences in the estimated area of class I land between evaluation procedures A and B are substantial in terms of being more than 25% for two out of six major grassland regions, which means that the compound units can have great impact on assessments being made. The difference of 27% in the Western Grassland region does not affect the final conclusion on injection possibilities in that region because the optimistic estimate (B) is still low. The range of 32% for the Eastern Sand region does question the usefulness of the results for that particular region.

DISCUSSION AND CONCLUSIONS

About 40% to 60% of Dutch rural land is suitable for slurry injection. However, in four out of six major Dutch grassland regions, the area of suited agricultural land is less than 50%, and in half of the regions this area is even less than 40%. Thus, apart from some sandy grassland regions, possibilities for slurry injection are relatively small. Based on our study the Dutch government, therefore, did not include injection of slurry on grassland for the entire Netherlands in its environmental legislation. Instead, the government is now examining region-specific measures and encourages the design of adapted injection equipment (e.g. shallow injector, swad injector, umbilical system).

Usually land evaluation methods explore potential land use options and hence the results cannot be comprehensively validated against reality (e.g. Rossiter, 1990). Results of experimental trials are locally obtainable to validate the estimates for a small number of land mapping units. The land evaluation results must be considered valid if they accurately reflect the land evaluator's best judgement. An independent evaluation by several experts is one way to examine reliability. Usually this cannot be realized because resources are limited. The reliability of the assessment of possibilities for slurry injection in our study could be compared with results produced in an earlier stage of the project. The results of both stages were acquired by different persons and were therefore fit to be used for comparison. The evaluation carried out in the first stage was performed in the conventional way, i.e. by hand, and more soil information was used at the time. For 20% to 25% of the land mapping units, different suitability classes (distinction of five classes) were found and for 5% the difference amounted up to two classes (maximum). This result reflects the reliability of the much faster ALES-based approach.

Our study showed that a combined use of GIS and computer-captured expert knowledge in qualitative land evaluation methods proved to be useful to explore land use options. General results are quickly obtained, which reduces the number of possible land use options. Within a relatively short time-period policy-makers and researchers can focus on remaining, more promising options. Finally, when a few feasible options remain, more detailed results can be obtained by applying quantitative evaluation methods.

A prerequisite to acquire quick evaluation results is linkage with a GIS as demonstrated in our study. Geographical information systems have already been established in many countries comprising maps and associated data on natural resources.

Especially small-scale maps, stored in a GIS, are useful when quick but generalized results are required for large areas of land. Although the land characteristics of these maps are broadly defined and many of the units are compound by nature, our study on slurry injection demonstrated that results obtained were quite useful for subsequent decision-making.

ACKNOWLEDGEMENTS

We thank Dr. D.G. Rossiter (Cornell University, New York State), Dr. J. Bouma (Agricultural University, Wageningen) and Ir. M.J.D. Hack-ten Broeke (Winand Staring Centre, Wageningen) for constructive comments on an earlier version of this paper. The authors wish to recognize Rini Schuiling's invaluable assistance during compilation of the maps.

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4 ASSESSMENT OF SOIL MOISTURE DEFICIT AND SOIL AERATION BY QUANTITATIVE EVALUATION PROCEDURES AS OPPOSED TO QUALITATIVE METHODS

Published in J. Bouma and A.K. Bregt (eds.), Land Qualities in Space and Time; proceedings of a symposium organized by the International Society of Soil Science (ISSS), Wageningen, the Netherlands, 22-26 August 1988. Pudoc, Wageningen, 1989, pp. 189-192.

ASSESSMENT OF SOIL MOISTURE DEFICIT AND SOIL AERATION BY QUANTITATIVE EVALUATION PROCEDURES AS OPPOSED TO QUALITATIVE METHODS

H.A.J. van Lanen* and J. Bouma**

* Netherlands Soil Survey Institute, Wageningen, the Netherlands
** Agricultural University, Wageningen, the Netherlands

Summary

Qualitative and quantitative land evaluation procedures are applied to assess the land qualities moisture deficit and aeration for two soil types and several water-table classes. As a part of quantitative procedures, the use of dynamic simulation models allows a more extensive quantitative expression of land qualities, including temporal variability, and a more comprehensive evaluation of potential situations than the qualitative methods.

Keywords: qualitative and quantitative land evaluation methods, dynamic simulation models, soil moisture deficit, soil aeration.

Introduction

Dutch agriculture is now facing problems of surplus production. Furthermore, intensive cropping, which mainly includes wheat, potatoes and sugar beets in rotation, has resulted in a deterioration of soil structure and too high a population of nematodes and soil fungi. Policy is changing and farmers have to adapt their production systems. More market-oriented production systems have to be developed that have no adverse effects on nature and environment (e.g. reduction in nutrient losses). This new policy will alter land use (e.g. zoning of production, set-aside of land, and timber production). Conflicting situations may arise. Policy-making, therefore, should be based on objective and scientifically developed land evaluation methods. Descriptive, qualitative evaluation systems produce quick but general answers. As a first approximation they are helpful, but more quantitative information is generally needed. This may be provided by quantitative procedures. A large number of crops and a wide range of site conditions, both actual and potential, can be evaluated quantitatively.

The aim of this paper is to show differences between quantitative and qualitative land evaluation procedures. The land qualities moisture deficit and aeration will be used as examples. Emphasis is laid on temporal variability, expressing the range in weather conditions at a specific location.

Methods and materials

The simplest qualitative land evaluation procedures are purely descriptive. Land qualities are expressed in classes, such as good, moderate or bad. The more sophisticated qualitative methods, sometimes called 'semi-quantitative', already provide quantitative expressions for some land qualities, which have been derived from measured data, such as moisture retention and climatic data. This can be seen as a gradual transition to quantitative procedures. The essential difference between qualitative and quantitative procedures is that the latter comprise the application of dynamic simulation models.

Qualitative land evaluation procedures

This paper only deals with land qualities associated with water shortage or water excess. Moreover, only temporal variability will be discussed and no spatial aspects. Plant-available water (-5 kPa to -1600 kPa), moisture supply capacity (plant-available water plus capillary rise), and soil droughtiness (plant-available water minus potential precipitation deficit) will be calculated as measures for drought susceptibility. Air capacity (0 to -5 kPa), drainage status (related to water-table), and wetness class (integration of number of field capacity days, gley features and depth of impermeable layer) will be used for susceptibility to water excess. For a more detailed description of the assessment of the land qualities the reader is referred to McKeague et al. (1984).

Quantitative land evaluation procedures

Simulation of water flow and evapotranspiration by dynamic simulation models (e.g. Belmans et al., 1983) plays a prominent part in determining the land qualities moisture deficit and aeration. Land characteristics are either directly used as model input (e.g. horizont thickness and rootable depth) or converted by pedofunctions into land properties (e.g. moisture retention and hydraulic conductivity data) to feed the model. Moreover, non-land data, such as crop and weather information, are needed to perform the simulation. Variability in weather conditions is taken into account by using a thirty years' record of meteorological data. The model computes, among other things, potential and actual transpirations on a daily basis as well as air-filled porosities at various depths. Moisture deficit occurs when actual transpiration is smaller than potential transpiration. Inadequate aeration occurs when the air-filled porosity at a certain depth is lower than a soil-specific threshold value (Bakker et al., 1987). Land qualities are described with a probability distribution. Probability of occurrence of a moisture deficit or an adequate aeration is derived from an analysis of the daily results of the simulation of thirty years. This procedure is widely discussed elsewhere (Bouma & Van Lanen, 1987; Van Lanen et al., 1987).

Crop, soils and water-table classes

The land qualities moisture deficit and aeration are determined for two soil types, which are classified as Typic Fluvaquents. The soils are located in the south-western part of the Netherlands and are mainly in use as arable land. Therefore, a potato crop is used to illustrate the procedures. The first soil type (indicated by A) consists of 60 cm of sandy loam overlying sand and the second type (indicated by B) consists entirely of sandy loam. Both soils are calcareous and have topsoils of about 30 cm with organic matter contents of about 2%. Water-table classes are distinguished, which are charaterized by the mean highest (MHW) and the mean lowest water-tables (MLW). In these soils three classes occur, namely IV, VI and VII. These classes have MHWs of 50, 75 and 110 cm and MLWs of 120, 160 and 190 cm below soil surface respectively.

Results and discussion

The results of the qualitative land evaluation procedures are listed in Table 1. In the upper part, land qualities related to drought susceptibility are given and in the lower part those related to water excess.

The results of the quantitative procedure are presented in Figures 1a (moisture deficit) and 1b (aeration). The assessment of the land qualities is carried out for both soil types A and B and several water-table classes. The land qualities related to water shortage are determined for water-table classes VI and VII, and those related to water excess for classes IV and VI.

Table 1. Assessment of some water-associated land qualities for two soil types (A and B) and several water-table classes (IV, VI and VII) by qualitative methods.

Water shortage land qualities (mm)	A		B	
	VI	VII	VI	VII
plant-available water	100	100	115	115
moisture supply capacity	100-150	100-150	> 200	150-200
soil droughtiness	30	30	45	45

Water excess land qualities	A		B	
	IV	VI	IV	VI
air capacity (vol.%)	7	7	8	8
drainage status	2	2	2	2
wetness class	III-VI	III-VI	III-VI	III-VI

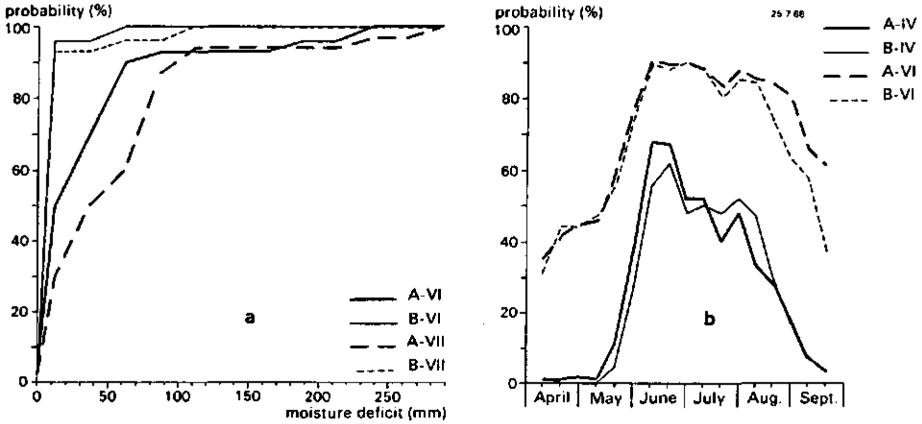

Fig. 1. Probabilities of occurrence of a moisture deficit (mm) for the entire growing season (a) and adequate soil aeration (days per ten days) (b) for two soil types (A and B) and several water-table classes (IV, VI, and VII).

In 9 out of 10 years the moisture deficit of the potato crop grown on soil type B is less than 20 mm. Hardly do any differences occur between the water-table classes (Fig. 1a). The moisture deficits in soil type A are higher than those in B; in 9 out of 10 years the deficits are less than 70 mm for water-table class VI and 110 mm for class VII. The maximum deficits are about 120 mm in soil type B and about 250 mm in A. Temporal variability, as induced by variable weather conditions, is not accounted for by the qualitative methods (Table 1). Plant-available water is used without taking into account climatic differences. The moisture supply capacity and soil droughtiness are in a way adjusted to soil, crop and climate. In comparison with the quantitative procedures, the results of qualitative methods only refer to one specific, usually an average or a typically dry, climatic situation. Furthermore, the approximation is much simpler. For instance, irregular rainfall distribution (time step equals one growing season) and increasing rooting depth for spring-sown crops are not taken into account.

Between the soil types A and B no great differences in aeration occur. Significant differences occur, however, between the water-table classes IV and VI. From June to September aeration is adequate in 9 out of 10 days in soils with water-table class VI (on an average), but this is not more than 5 out of 10 days in soils with class IV (Fig. 1b). At the start and the end of the growing season, aeration is less than in the mid-season. The land qualities defined by the qualitative methods do not supply temporal variability. Moreover, the distinct differences between the water-table classes are not characterized (Table 1). Therefore, potential situations, such as drainage measures, cannot be properly evaluated by the land qualities assessed by qualitative methods. Quantitative procedures as opposed to qualitative methods allow: (i) a more extensive quantitative expression of land qualities, including temporal variability; (ii) a more comprehensive evaluation of potential situations, and (iii) no arbitrary weighing of land charateristics to derive land qualities.

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5 COMPARING QUALITATIVE AND QUANTITATIVE PHYSICAL LAND EVALUATIONS USING THE ASSESSMENT OF THE GROWING POTENTIAL FOR SUGAR-BEET IN THE EUROPEAN COMMUNITIES

Submitted for publication in Soil Use and Management

Comparing Qualitative and Quantitative Physical Land Evaluations Using the Assessment of the Growing Potential for Sugar-Beet in the European Communities

H.A.J. VAN LANEN[1], C.A. VAN DIEPEN[1], G.J. REINDS[1] & G.H.J. DE KONING[1]

[1] *The Winand Staring Centre for Integrated Land, Soil and*
Water Research, P.O. Box 125, 6700 AC Wageningen
(the Netherlands)

ABSTRACT

Qualitative and quantitative physical land evaluations differ in their technical procedures, viz. use of expert knowledge versus process-oriented simulation models. This paper compares the results of both procedures using the growing potential for sugar-beet in the European Communities. Qualitative procedures yield suitability expressions such as land being well suited or marginally suited for a given land use. Less than 30% of EC land was found to be well suited or moderately suited under water-limited conditions. No quantitative expressions for the crop yield potential are, however, produced. The quantitative procedure provides suitability in terms of average crop yield and its temporal variability. Water-limited and potential dry-matter yields of sugar-beet were estimated to vary from 3.5 to 20 t ha^{-1} yr^{-1}, and from 6 to 25 t ha^{-1} yr^{-1}, respectively. Comparing results of the qualitative and quantitative procedures for regions showed that the suitability classes obtained by the former can be characterized by different yield distributions derived from the latter. These yield assessments revealed that results of qualitative physical land evaluation procedures aiming at assessing the yield potential are only meaningful when they are linked to agro-climatic zones. Furthermore, comparing both procedures demonstrated that some moderate restrictions, which generally can be compensated for by adequate farm management, are not incorporated in the quantitative procedure.

INTRODUCTION

All over the world agricultural production systems are changing in response to increasing social and ecological demands. Rational decisions on the modifications in production systems should be based on a comprehensive analysis of the very production systems and the potentials of the natural resources, e.g. climate, soils, topography, and hydrology. Physical land evaluation can provide information on the potentials and constraints for a defined land use type in terms of crop performance as far as affected by the physical environment.

There are different levels of detail in the technical procedures of physical land evaluation, ranging from simple to detailed (Bouma, 1989). Qualitative physical land evaluation methods are based on relatively simple procedures, viz. the use of farmers' experience and expert knowledge. Quantitative physical evaluation methods, on the other hand, comprise more detailed technical procedures, such as computer models simulating soil-water flow, crop growth, and nutrient uptake. Qualitative methods usually require less input data than the quantitative ones; consequently the results are less specific (e.g. Dent & Young, 1981; Bouma, 1989; Van Lanen & Bouma, 1989; Van Diepen et al., 1991). The questions to be answered, the availability of data, and the possibility to collect additional data determine which type of physical land evaluation is most appropriate in a study. For example, in an initial stage of regional agricultural planning or in the exploration phase of a major change in farm management practices, when a broad spectrum of alternatives is still being explored, results of qualitative methods are usually adequate. In subsequent planning phases, however, more detailed assessments of potentials and constraints, including expressions of their spatial and temporal variabilities, are required (e.g. Fresco et al., 1990).

The objective of this paper is: (i) to describe qualitative and quantitative physical land evaluation methods, and (ii) to compare differences between results obtained by both methods for the growing potential for sugar-beet in the European Communities (EC). The comparison is restricted to the overall suitability in terms of the sugar-beet yield potential. Differences between water-associated land qualities obtained with both methods are discussed elsewhere (Van Lanen & Bouma 1989). This study was conducted in the context of assessing regional production potentials for a number of crops in the EC (Van Lanen et al., in prep.).

MATERIALS

Geographical distributions of soil and climate units and their associated attribute data were used both by the qualitative and quantitative physical land evaluation methods. As the maps and attribute data had to cover the whole European Communities (EC), only small-scale maps and associated data bases were used.

In this study we focus on describing the evaluation methods and comparing the results. Therefore, the materials used are only broadly explained; Reinds et al. (in press) provide a detailed description.

Soil data

The EC Soil Map, scale 1 : 1 000 000 (Commission, 1985) was used. This map distinguishes 546 soil associations, including soil phases, which are distributed over more than 15 000 delineations. Each soil association contains a dominant soil unit, associated units, and inclusions. The availability of soil attribute data restricted the evaluation to the dominant soil units, which cover over 60% of EC area. The evaluation is likely to be representative for a larger area, because not all pedogenetic differences between the dominant soil unit, the associated units, or inclusions of a soil association are functional in terms of sugar-beet yield potential. Land characteristics for the dominant soil unit were either provided by the map legend (e.g. soil texture and slope class), or were derived through an interpretation procedure (e.g. drainage class, soil depth). For instance, the drainage class was deduced from the pedogenetic name, which is based on hydromorphic features in the soil profile, in combination with the soil texture. Furthermore, water retention data were allocated to the unit taking into account soil texture.

Agro-climatic data

An agro-climatic map was compiled, which comprises 109 agro-climatic regions. A representative meteorological station was allocated to each zone, assuming no climatic variation within the zone. Year-to-year weather variation, which had to be known for applying the quantitative evaluation method, was considered by using a 26 years' record of monthly weather data for each station. The data set comprises minimum temperature, maximum temperature, global radiation, wind speed, vapour pressure, rainfall, and number of rainy days. The long-term averages of these variables were calculated from these historical records. Moreover, the average annual precipitation deficit was computed, which has been defined as the difference between the monthly potential evapotranspiration of a reference crop and rainfall. Only the values of the months with a deficit were summed (cf. Mohrmann & Kessler, 1959). Average figures were required in qualitative evaluation.

The soil and climate data were stored in a geographical information system (GIS). A map overlay was carried out using basic maps, such as the soil and agro-climatic maps, which resulted in a compound map with land evaluation units (LEUs). About 4200 LEUs were distinguished, distributed over more than 22 000 delineations (Bulens et al., 1990). The physical land evaluation methods were applied to each of these LEUs.

METHODS

Qualitative and quantitative physical land evaluation methods were applied to assess the suitability of EC land for sugar-beet growing to allow a comparison of the results of both land evaluation methods.

The qualitative evaluation method was applied to all LEUs, whereas the quantitative method was applied to potentially suited LEUs only, i.e. units without severe limitations for growing sugar-beet. Selecting these potentially suited LEUs required a separate application of a qualitative procedure. Thus, qualitative methods were applied in two ways: (1) fully qualitative evaluation of all LEUs for growing sugar-beet, and (2) screening all LEUs to select those LEUs that are potentially suited for sugar-beets as the first step of a so-called mixed qualitative/quantitative land evaluation procedure (Van Lanen et al., 1989)

Qualitative land evaluation

Qualitative physical land evaluation methods indicate the degree of suitability of land for a particular land use in qualitative terms (e.g. well suited, marginally suited). The principles have been outlined by the Food and Agricultural Organisation (Food, 1976).

Use of expert knowledge is characteristic of qualitative methods. The Automated Land Evaluation System, ALES (Rossiter, 1990), was used to capture the expert knowledge in a computer system. With ALES, decision trees can be defined to represent the expert knowledge. These trees are structured representations of a reasoning process needed to combine basic data and expert knowledge to reach decisions. In our study, the process eventually led to a decision on the overall suitability of a LEU for sugar-beet growing.

The following steps were executed: (1) determining land use requirements derived from the land use type; (2) selecting relevant land characteristics (LCs; Food, 1976) that characterize the land resources of a LEU; (3) defining land qualities (LQs; Food, 1976) and inferring these from LCs using a decision tree for each LQ; ratings or severity levels of LQs were established for each LEU, for instance no, moderate, or severe restrictions; the severity level specifies the degree to which a LEU meets the requirements of the land use type; and (4) combining LQs using a decision tree to deduce the overall physical suitability. In our study some LCs had such a distinct influence on the overall suitability that they were not incorporated in an LQ. A severity level for these LCs was assessed similarly to the LQs in step 3 and, next, the LCs were directly used together with the LQs in the evaluation of the overall suitability (step 4).

Sugar-beet was supposed to be one of the products of a land utilization type comprising a general arable farming production system. This system is characterized by high inputs, e.g. a high mechanization level and an adequate application of nutrients. Weeds and diseases are controlled when required. In this study evaluating the potentials of EC land was restricted to the water-limited production only, i.e. no irrigation is supposed to be applied.

In our study, the land use requirements of sugar-beet and the knowledge to define the decision trees for the LQs and the overall suitability were obtained from Dent & Young (1981), Sys (1985), Kromwijk & Bosch (1986), Van Soesbergen et al. (1986), De la Rosa & Moreira (1987) and Hough (1990). For instance, land located on steep slopes (> 15%) or land with an excessive stone content (> 35% stones greater than 7.5 cm, or > 35% gravel) was considered unsuited for mechanized sugar-beet growing. Moreover, excluding land on slopes steeper than 15% minimizes negative consequences of water erosion on arable land. Seed-bed preparation and harvest of sugar-beet require well-drained, medium- to light-textured soils, especially in the humid areas. Thus, certain clay soils and poorly drained land were evaluated as unsuited. Sugar-beet is fairly tolerant of soil salinity, which implies that only soils with an electric conductivity of more than 4 mS/cm were evaluated as unsuited. In the growing period the crop needs approximately 450-550 mm water for unrestricted growth. The sum of rainfall and soil-moisture supply capacity needed to be higher than these amounts; otherwise, the LEU was supposed to be unsuited.

For the fully qualitative evaluation procedure, three LQs were identified as being relevant: drought susceptibility, soil aeration, and soil-physical quality. The last LQ has a compound nature which implicitly includes aspects of trafficability, workability, and harvestability as recognized by FAO (Food, 1976). As an example of how severity levels of a LQ were derived from LCs, the relatively simple decision tree for the LQ soil aeration is given in Figure 1. In this decision tree the LQ soil aeration is derived from the LC soil drainage. When the soil is imperfectly drained, the LCs soil texture and annual precipitation deficit are considered. Finally, a decision is reached on the severity level of the LQ soil aeration, e.g. no limitations.

Besides the above-mentioned three LQs, the LCs slope, cation exchange capacity (CEC), salinity, alkalinity, and presence of gypsum were used to assess the overall physical suitability of land for growing sugar-beet. The LQs and LCs used, and the criteria used to decide on, are summarized in Annex I. Because of the size of the decision tree for the LQ drought susceptibility, only part of the criteria are given, viz. those for the situation with an annual precipitation deficit of 200-300 mm. For more humid or drier conditions the severity levels of this LQ were adjusted depending on the soil texture, soil depth, drainage class, and presence of soil phases.

The overall suitability was expressed in three classes, namely well suited land (class I), moderately suited land (class II), and the group of marginally suited and unsuited land (class III). Class II land was expected to have a crop yield less than 80% of the yield under optimal conditions, but the required inputs are likely to be practicable and economic. Class III land was assumed to have severe limitations that can rarely or never be overcome by an economic use of inputs or management practices (e.g. Dent & Young, 1981).

The maximum limitation method (e.g. Rossiter, 1990) was applied to assess the overall physical suitability from the LQs and LCs considered. This implies that the LQ or the LC with the most severe restriction determines the suitability class irrespective of the severity levels of the other LQs and LCs.

As mentioned above, qualitative land evaluation was also applied as the first step in a mixed qualitative/quantitative procedure to select LEUs without obvious, serious restrictions for sugar-beet growing (Reinds & Van Lanen, in press). The LEUs were screened for critical crop- and management-specific requirements. LEUs were evaluated as potentially suited for sugar-beet growing at mechanized farms when they met the requirements for class II land, i.e. LEUs with no or moderate limitations (Annex I). However, one distinct difference with the fully qualitative

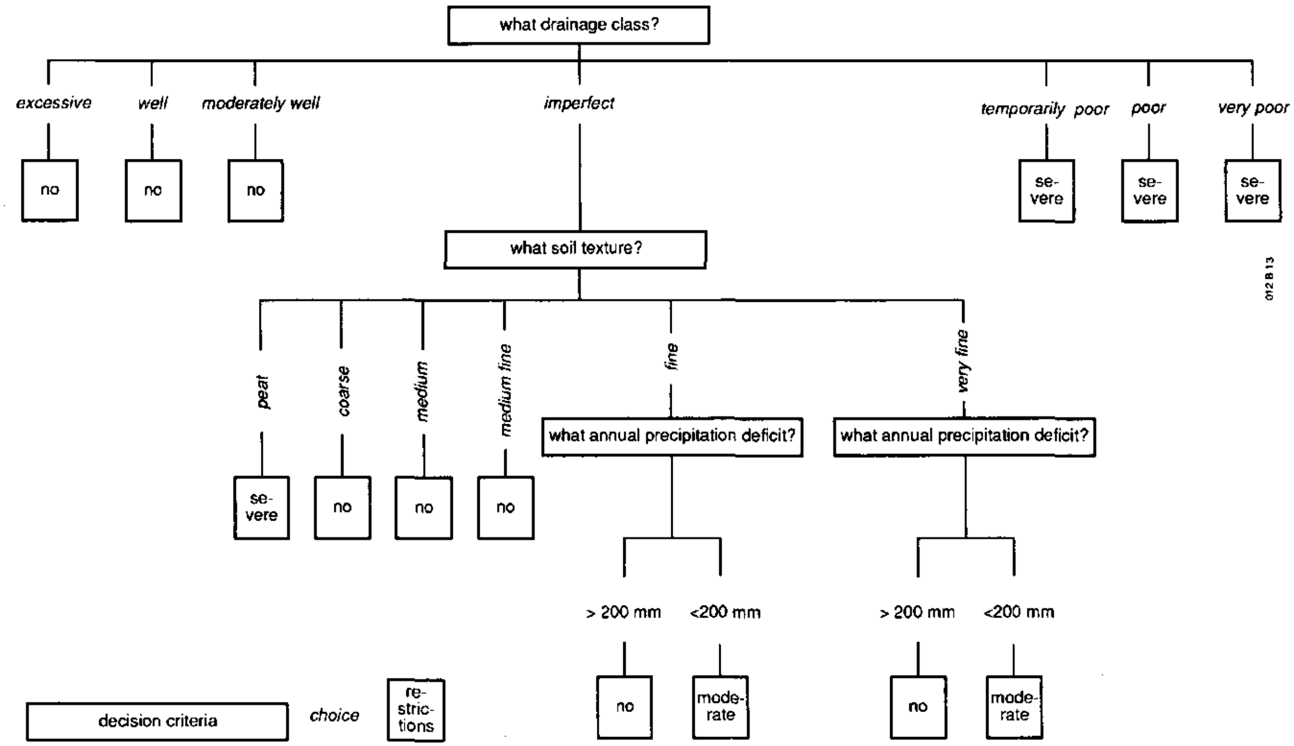

Fig. 1 Decision tree for the qualitative evaluation of land on limitations of the land quality soil aeration.

evaluation prevailed: no drought susceptibility criteria were included in the selection of potentially suited LEUs. This means that land with a high drought susceptibility, but without other severe limitations, was evaluated as potentially suited by the mixed qualitative/quantitative procedure. Thus for some level, well-drained, deep, coarse-textured soils in the drier regions, which were evaluated as marginally suited or unsuited according to the fully qualitative method (class III land), the water-limited sugar-beet yield was still simulated by the quantitative method (Fig. 2). These LEUs were considered potentially suited, because they might have a high yield potential under irrigated conditions, which was relevant to another study not reported here.

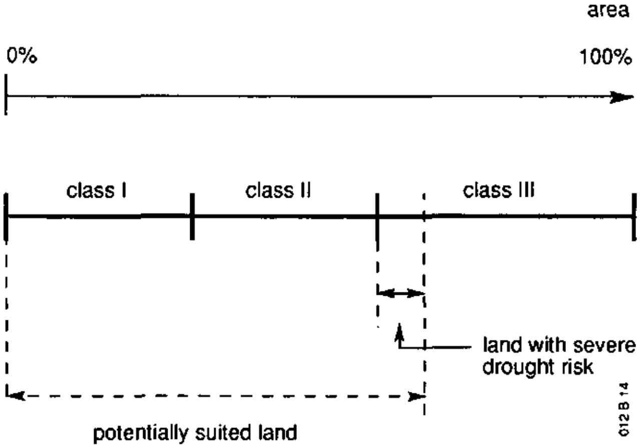

Fig. 2 Relationship between potentially suited land as used by the quantitative evaluation procedure and the three suitability classes distinguished by the fully qualitative procedure.

Decision rules were captured in a computer system, and subsequently all LEUs were automatically screened, resulting in a list of potentially suited LEUs and areas of potentially suited land. Subsequently, a quantitative method was applied to the potentially suited LEUs.

Quantitative land evaluation

Quantitative physical land evaluation methods yield quantitative expressions for crop production, such as crop yield in kg dry matter per unit area, and associated inputs (e.g. m^3 water, kg nutrients). Computer models simulating the soil-water balance and associated crop growth and yield are essential parts (e.g. Dumanski & Onofrei, 1989; Van Diepen et al., 1989).

In this study we used the WOFOST model. The concepts and the parameters of this crop growth model are based on decades of extensive crop research (Van Keulen & Wolf, 1986; Van Diepen et al., 1989). The model was applied to the potentially suited LEUs only in the second step of the mixed qualitative/quantitative land evaluation approach. WOFOST simulates the growth and yield of a crop and the soil-water balance in daily time steps under prevailing weather and site conditions. The major simulated processes in the crop submodel after emergence are phenological development, light interception, assimilation, respiration, partitioning of dry-matter increase over plant organs, and transpiration. The various parameters for sugar-beet were obtained from Van Heemst (1988) and Spitters et al. (1989). One sugar-beet variety was used to allow a better assessment of the impact of soil and climate throughout the EC. The model, however, was adapted to regional conditions by specifying different sowing and harvesting dates (De Koning et al., in press).

Crop yields were calculated for the water-limited production situation. However, before the water-limited yield could be simulated the potential crop yield was computed. The potential crop yield is the integrated expression of agro-climatic conditions, i.e. the influence of radiation and temperature on growth of a particular crop cultivar. When the potential transpiration is hampered by the transient soil-water status, daily potential crop growth is reduced. The water-limited yield includes the effects of drought stress and waterlogging by using soil and weather data.

Long-term average crop yields as well as temporal variability were obtained by running WOFOST for a period of 26 years using historical records of weather data. WOFOST only simulates dry-matter increase and does not account for the sugar content of the tubers.

The results of the quantitative evaluation approach are not primarily intended for predicting real-time crop yields. Instead they are meant to explore the impact of the crop growth potential on land use options or promising farm management strategies by comparing alternatives (e.g. Van Lanen et al., in prep.).

SUITABILITY OF EC LAND FOR GROWING SUGAR-BEET

Qualitative assessment

The physical suitability of each LEU was determined with the fully qualitative evaluation procedure using ALES, and expressed in three suitability classes. Because of the great number of LEUs, results of individual LEUs are not discussed. The results of the LEUs, however, were stored in the GIS and aggregated for the member states and the entire EC. This implied computing

Table I Relative area (%) of well suited (class I), moderately suited (class II), and marginally suited or unsuited land (class III) according to the fully qualitative procedure, and potentially suited land according to the mixed qualitative/quantitative procedure, for growing sugar-beet in the EC

Country	Class I	Class II	Class III	Potentially suited
West Germany	20	20	60	43
France	11	22	67	40
Italy	3	2	95	13
The Netherlands	16	47	37	63
Belgium	10	48	42	59
Luxembourg	3	3	94	15
United Kingdom	5	16	79	29
Ireland	12	33	55	47
Denmark	7	29	64	90
Greece	5	0	95	5
Spain	6	1	93	8
Portugal	1	2	97	16
EC	8	14	78	28

the relative area of each suitability class for each of the countries considered. In the EC about 8% of the land was estimated to be well suited for growing sugar-beet under water-limited conditions, whereas 78% was expected to be marginally suited or unsuited. About 14% of EC land was estimated to be moderately suited (Table I). Severe restrictions of the soil-physical quality and drought susceptibility were the main reasons to find EC land marginally suited or unsuited, viz. 60% and 50% of EC land respectively (Fig. 3b). Large areas suffer from severe restrictions of both land qualities, sometimes combined with severe slope restrictions as well, i.e. 40% of EC land (first two bars, Fig. 3a). Class I and class II land cover more than 50%

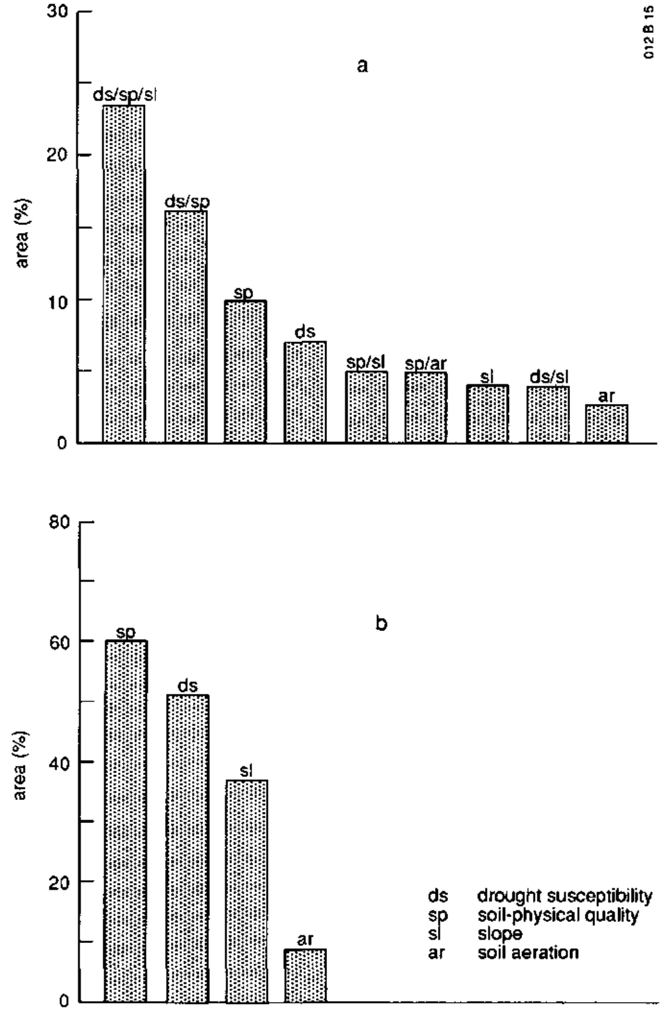

Fig. 3 Relative area (% of EC) covered by land with particular types of major limitations causing marginally or unsuited land for sugar-beet growing: (a) severe limitations of land qualities or combinations of these (actual situation), and (b) severe limitations of individual land qualities.

of the Netherlands and Belgium, but less than 10% of the Mediterranean countries (Table I).

The estimated relatively high percentages of class III land in some EC countries, especially in the southern member states, confirmed earlier assessments by Buringh et al. (1979) and Lee (1987).

Quantitative assessment

Regional differences in simulated yields

The average potential sugar-beet yield simulated by WOFOST was calculated for each potentially suited LEU (De Koning et al., in press). The simulated yield refers to the weight, expressed as dry matter, of the main root in which the sugar is stored. The area of potentially suited land equals the areas of class I and class II land as had been assessed by the fully qualitative evaluation method plus a small part of class III land suffering from drought stress only (Table I and Fig. 2).

The average water-limited sugar-beet yields calculated for each potentially suited LEU were spatially aggregated to an average figure for the agro-climatic regions (Fig. 4). Spatial aggregation implied calculating the weighted average yield considering the acreages and simulated yields of the potentially suited LEUs occurring in a region. So, the yields in Figure 4 apply to a limited

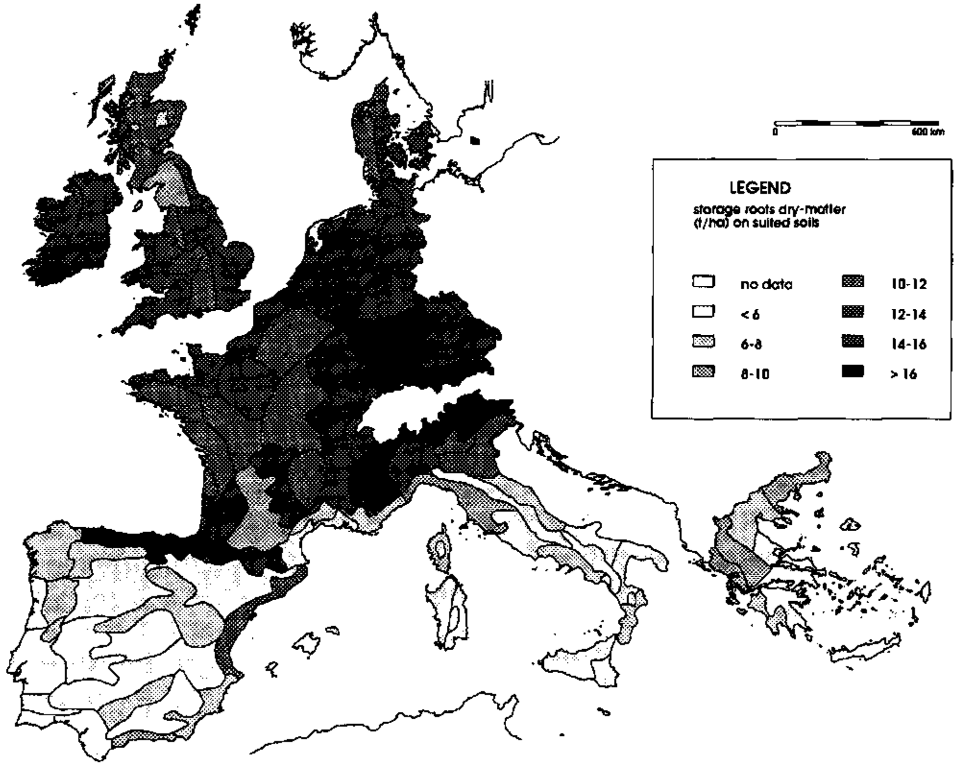

Fig. 4 Simulated average water-limited sugar-beet yield for agro-climatic regions in the EC; figures apply to potentially suited land only.

part of the agro-climatic regions, viz. the potentially suited areas only. These potentially suited areas cover 5% to 90% of the member states (Table I), and 1% to 90% of the area of the agro-climatic regions (De Koning et al., in press). The water-limited yield is determined by the potential yield level, rainfall, potential transpiration, and soil characteristics. The average potential dry-matter yields within the agro-climatic regions of the EC were found to vary from 6 t ha^{-1} yr^{-1} in Scotland to a maximum of slightly over 25 t ha^{-1} yr^{-1} in northern Portugal (De Koning et al., in press). The average water-limited yields range from about 3.5 t ha^{-1} yr^{-1} in certain regions in Portugal to nearly 20 t ha^{-1} yr^{-1} in northern Spain. Large areas with water-limited yields lower than 8 t ha^{-1} yr^{-1} occur in the Iberian Peninsula, in Italy, Greece, and in the French Mediterranean region. Further north, the water-limited dry-matter yields approximate the potential yields and are in the order of magnitude of 15 t ha^{-1} yr^{-1}.

Italian (Alvino, 1983; De Caro & Cucci, 1986), French (Institut, 1988) and Dutch (Van der Schans & Drenth, 1989; Smit et al., 1989) investigations confirm that simulated yields in our study are attainable.

Temporal variability of simulated yields

Average sugar-beet yields for agro-climatic regions were computed by averaging the simulated yields of each of the relevant LEUs over the 26 years' period. Average figures give an overall impression of the regional production potential. To risk analysis, however, inter-year yield variation caused by weather conditions is relevant (e.g. Dumanski & Onofrei, 1989). The simulated yield figures of the individual years allow occurrence probabilities of sugar-beet yields for different LEUs to be explored (Fig. 5). For example, in the Birmingham region in 80% of the years the water-limited dry-matter yield was found to vary between 10 and 15 t ha^{-1} yr^{-1}. In the Bordeaux region, weather differences, however, are estimated to cause a greater range in annual yields, viz. between 5.5 and 19 t ha^{-1} yr^{-1} in 80% of the years. So without irrigation, risk-avoiding farmers find better opportunities in the Birmingham region than in the Bordeaux region.

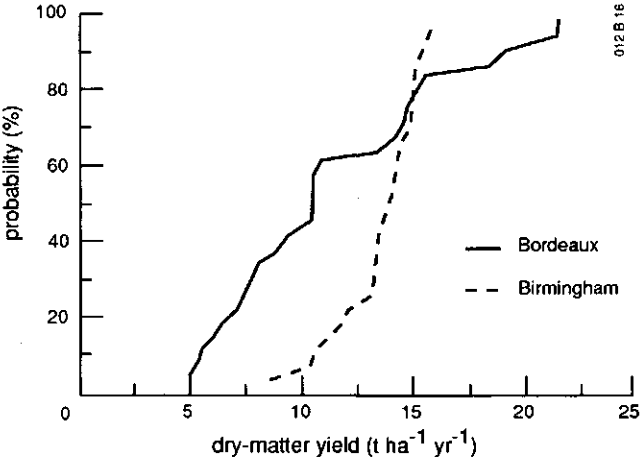

Fig. 5 Temporal variability of simulated sugar-beet yield for medium-textured Dystric-Cambisols in the Birmingham region (England), and the Bordeaux region (France).

COMPARING QUALITATIVE AND QUANTITATIVE METHODS

The results of the qualitative and quantitative physical land evaluation methods were compared for each potentially suited land evaluation unit (LEU). Thus, the comparison was restricted to 28% of the EC area (Table I). All other land was evaluated as marginally suited or unsuited. For each potentially suited LEU, the simulated sugar-beet yield was compared with the suitability class obtained by the fully qualitative land evaluation method.

When the LEUs occurring in a region are considered, yield distributions for that particular region can be computed for each of the suitability classes. Such yield distributions were calculated for the EC and the individual member states. In the EC, the simulated water-limited dry-matter

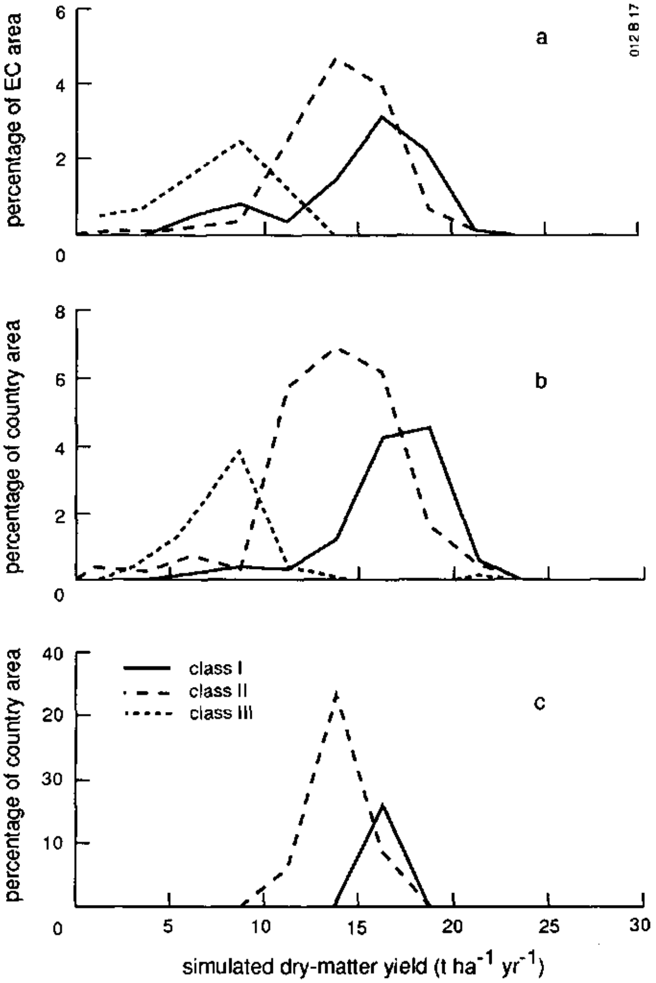

Fig. 6 Distribution of the simulated water-limited sugar-beet yield for three suitability classes. a: European Communities, b: France, and c: the Netherlands.

yield of the well suited LEUs (class I land) in 80% of the cases varied between 11 and 21 t ha^{-1} yr^{-1} (Fig. 6a). For the moderately suited LEUs (class II land) this yield ranged from 8.5 to 18 t ha^{-1} yr^{-1}, and for the marginally suited and unsuited LEUs (class III land) from 3 to 12.5 t ha^{-1} yr^{-1}. As the areas of the LEUs vary considerably, distributions were based on the areaof the LEUs occurring in a specific yield class, instead of solely on the number of LEUs as in conventional frequency distribution analysis.

The yield distributions (Fig. 6) of land evaluated as class III land by the fully qualitative procedure because of severe drought susceptibility confirm the relatively low yield potential of such land. This comparison refers to a small fraction of class III land (Table I), namely that part which has no other severe limitations than drought susceptibility, and for that reason was evaluated as potentially suited by the mixed qualitative/quantitative land evaluation procedure (Fig. 2).

Analysing of the individual member states showed that in France the dry-matter yields for class I, class II, and class III land varied mainly between 12 and 21, 9 and 19, and 3 and 11 t ha^{-1} yr^{-1}, respectively (Fig. 6b). The medians of the yield distributions for these three suitability classes were 17.5, 13.5 and 8 t ha^{-1} yr^{-1}. The medians for the other EC member states are given in Table II. Although the yield distributions of the suitability classes overlap, the decreasing medians of the suitability classes correspond well with the ranking of the suitability classes from well suited to unsuited, as illustrated for the individual member states and the EC as a whole (Table II).

Table II Median of simulated water-limited dry-matter yield of sugar-beet (t ha^{-1} yr^{-1}) derived from the quantitative method for the three suitability classes (I = well suited, II = moderately suited, III = marginally suited or unsuited), which were determined by the fully qualitative method

Country	Class I	Class II	Class III
West Germany	17.0	15.0	11.5[1)]
France	17.5	13.5	8.0
Italy	13.0	9.5	6.5
The Netherlands	16.0	14.0	-[2)]
Belgium	16.0	14.5	9.5
Luxembourg	17.5	17.5	9.5
United Kingdom	15.0	13.0	10.5
Ireland	14.5	14.0	11.0
Denmark	15.5	15.0	9.5
Greece	9.5	-	5.0
Spain	8.5	7.0	5.0
Portugal	8.5	8.0	2.0
EC	15.5	14.0	8.5

[1)] median of yield refers only to relatively small part of class III land which was evaluated as potentially suited in the quantitative evaluation approach despite severe drought risk

[2)] in that particular class no potentially suited land occurs that can be improved by irrigation only

The width of the distributions, and therefore the overlap, is partly caused by the different agro-climatic conditions prevailing within the EC or a member state. The width decreases when a member state is considered that is predominantly located in one agro-climatic region, such as the Netherlands (Fig. 6c). Most water-limited dry-matter yields of Dutch class II land were found to vary between 11.5 and 16 t ha^{-1} yr^{-1}, and for class I land it was evaluated to vary between 14 and 19 t ha^{-1} yr^{-1}. No yields were simulated for Dutch class III land, because no land evaluation units were evaluated as marginally suited or unsuited because of drought risk only. Of course, in the Netherlands marginally suited or unsuited land occurs owing to other causes. But this land was not included in the potentially suited land for reasons explained above.

Because of agro-climatic differences within the EC, the crop yield potential of well suited or moderately suited land significantly differs among the member states (Table II). In France the simulated median sugar-beet yield of class I land amounted 17.5 t ha^{-1} yr^{-1} dry matter, whereas in the north and the south the potential of class I land was estimated to drop to about 15 t ha^{-1} yr^{-1} and 9 t ha^{-1} yr^{-1}, respectively. In the northern member states the lower radiation and temperature are the main cause for the smaller potential of class I land, whereas in the southern member states sugar-beet on class I land will usually suffer from some water stress and in certain regions from high temperatures as well.

Although land characteristics such as temperature and radiation data were available for the agro-climatic regions, they were not accounted for in the fully qualitative procedure. The main reason for neglecting these data is the lack of expert knowledge of how to relate them straightforwardly with crop yield level (see also Lee, 1987).

The yield distributions for the suitability classes of the EC countries usually show a distinct difference between the yields of class III land and the yields of classes I and II (Fig. 6 and Table II). Furthermore, the lower limits of the yields of classes I and II differ as well (Figs. 6b and 6c), but the upper limit often coincides. Class II land, however, can only attain this upper yield limit, when some moderate restrictions, such as a low CEC, are taken into account by an appropriate farm management, which usually implies higher costs. For instance, about 2% of French land was allocated to class II by the fully qualitative evaluation method, because of a low CEC despite its high yield potential. The impact of a low CEC and some other moderate limitations, such as moderately steep slopes (8-15%), on farm management is hard to assess quantitatively. Moreover, this type of limitations was expected to be accounted for in a subsequent economic evaluation, because higher inputs might be considered.

CONCLUSIONS

According to the qualitative physical land evaluation method, about 22% of EC land was evaluated as moderately suited or well suited for growing sugar-beet under water-limited conditions (Table I). The reasoning process, based on expert knowledge (Fig. 1), allowed the nature of the limitations of land with restrictions to be specified (Fig. 3). A quantitative expression of the sugar-beet yield potential, however, cannot be produced by the qualitative methods. Conversely, quantitative physical land evaluation can produce these data. The simulated average water-limited sugar-beet yield on potentially suited land in the EC was predicted to vary between 3.5 and 20 t ha^{-1} yr^{-1} dry matter according to the quantitative physical land evaluation method (Fig. 4). The method also provided a quantitative assessment of temporal variability of crop yield considering 26 years' weather data, which is essential for risk analysis. In our study the quantitative evaluation method used crop yield as an integrated suitability criterion of a land unit. The nature of possible limitations that might cause a deviation from the potential yield, however, is not provided in this way. The detailed model output has to be thoroughly analysed to find which land characteristics are limiting. Sometimes a sensitivity analysis has to be performed to find the limiting characteristic.

Comparing the results of the qualitative evaluation method with those of the quantitative one for the potentially suited area showed that the suitability classes of the former can be clearly characterized by different yield distributions as obtained with the latter (Fig. 6 and Table II). Furthermore, the analysis clearly showed that the significance of well suited land or moderately suited land in terms of crop yield potential substantially differs among the agro-climatic zones (Table II). Therefore, applying qualitative physical land evaluation aiming at assessing the crop yield potential of large areas is only relevant to agro-climatic zones (e.g. Food, 1978; Stewart, 1981). This shortcoming of the fully qualitative evaluation procedure, as applied in our study and by many others (e.g. Lee, 1987), also implies that scenarios exploring regional crop production potential, such as the possible impact of global climate change on crop production, can only be adequately evaluated with quantitative methods.

Comparing the results of the fully qualitative and the quantitative methods revealed that some moderate restrictions, which can generally be compensated for by an adapted farm management, were not incorporated in the quantitative evaluation method. Adapting farm management, however, might require higher inputs. When moderate limitations, because of the increased inputs, are so important that they have to be included in the suitability assessment, an economic evaluation is necessary. Then, specific money values are applied to data from the quantitative physical land evaluation method, thereby obtaining the costs of inputs and value of production (e.g. Dent & Young, 1981).

ACKNOWLEDGEMENTS

The authors wish to thank J.D. Bulens for helping to compile the maps using ARC/INFO software and D.G. Rossiter (Cornell University) for expanding the ALES data base. A digitized EC soil map and a map with administrative regions were kindly supplied by the CORINE project team (CEC). In this context the support of Ir. J. Maes (CORINE) was invaluable.

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Annex 1 Severity levels[1)] of land qualities and land characteristics used in the full qualitative evaluation procedure to assess the growing potential for sugar-beet

Land quality: soil-physcial quality (not distinguished for moderate limitations)

Land characteristic	No limitations	Severe limitations
soil texture class[2)]	2-4	1, 5, 6
soil depth[3)]	2-6	1
soil phases[4)]	absent	present

Land quality: soil aeration[1)] (for seven drainage classes)

Soil texture	Very poor	Poor	Temporarily poor	Imperfect		Moderately well	Well	Excessive
				< 200[5)]	>200[5)]			
peat	3	3	3	3	3	-	-	-
coarse	3	3	3	1	1	1	1	1
medium	3	3	3	1	1	1	1	1
medium fine	3	3	3	1	1	1	1	1
fine	3	3	3	2	1	1	1	1
very fine	3	3	3	2	1	1	1	1

Land quality: drought susceptibility[1)] for annual precipitation deficit of 200-300 mm

Soil texture	Soil depth[3)]	No soil phase[4)], drainage class:							With soil phase[4)]
		very poor	poor	temp. poor	imperfect	mod. well	well	excessive	
peat	-	1	1	1	1	-	-	-	-
coarse and very fine	1	3	3	3	3	3	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	2	2	2	3	3	3	3
	4	1	1	1	1	3	3	3	3
	5	1	1	1	1	3	3	3	3
	6	1	1	1	1	3	3	3	3
medium, medium fine, and fine	1	3	3	3	3	3	3	3	3
	2	1	1	1	1	2	3	3	3
	3	1	1	1	1	2	3	3	3
	4	1	1	1	1	2	2	3	2
	5	1	1	1	1	2	2	3	2
	6	1	1	1	1	2	2	3	2

Land characteristics: salinity, alkalinity, CEC, gypsum, and slope

Land characteristic	No limitations	Moderate limitations	Severe limitations
salinity[6]	< 4	-	> 4
alkalinity[7]	< 15%	-	> 15%
CEC[8]	> 5	< 5	-
gypsum	absent	present	-
slope	< 8%	8-15%	> 15%

[1] 1 = no limitations, 2 = moderate limitations, 3 = severe limitations

[2] 1 = peat, 2 = coarse, 3 = medium, 4 = medium fine, 5 = fine, 6 = very fine

[3] 1 = very shallow (< 10 cm), 2 = shallow (10-40 cm), 3 = moderate (40-60 cm), 4 = moderately deep (60-80 cm), 5 = deep (80-120 cm), 6 = very deep (> 120 cm)

[4] soil phases such as gravelly, stony, lithic, and concrectionary

[5] average annual precipitation defict in mm

[6] estimated electric conductivity (mS/cm)

[7] exchangeable sodium percentage

[8] cation exchange capacity (mmol per 100 g soil)

6 A MIXED QUALITATIVE/QUANTITATIVE PHYSICAL LAND EVALUATION METHODOLOGY

Submitted for publication in Geoderma

A Mixed Qualitative/Quantitative Physical Land Evaluation Methodology

H.A.J. VAN LANEN[1)], M.J.D. HACK-TEN BROEKE[1)], J. BOUMA[2)] & W.J.M. DE GROOT[1)]

[1)] *The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen (the Netherlands)*

[2)] *Agricultural University, Department of Soil Science and Geology, P.O. Box 37, 6700 AA Wageningen (the Netherlands)*

ABSTRACT

In our study a mixed qualitative/quantitative physical land evaluation methodology is proposed. Broad, descriptive results of qualitative evaluation methods do not always support the land use planning process adequately. The mixed approach therefore comprises both qualitative and quantitative methods. The screening of land for serious constraints considering a defined land utilization type is carried out with qualitative methods based on computer-captured expert knowledge. Subsequently, the more comprehensive quantitative evaluation methods, using computer models to simulate soil-water flow and crop growth, can then be focused on remaining, potentially suited land.

The mixed qualitative/quantitative evaluation approach is exemplified with potato-growing in the Netherlands. Decision trees, illustrating how expert knowledge was used to infer potentially suited land from land qualities, are shown. About 65% of Dutch land was found to be potentially suited. This amount, however, depends on the soil map that was used, as is shown in our study. Both simple and complex simulation models were applied to a few Dutch areas having potentially suited land. The first screening pointed out that 90% of a sandy region in the east Netherlands was found to be potentially suited. Applying a simple model, which was a pedotransfer function in our example, to the remaining potentially suited area showed that no more than 15% of the area has an average potato yield depression of less than 10%. The other 75% of the region is moderately suited, i.e. has an average depression of more than 10%. Complex models were used for a quantitative analysis of two other areas with contrasting soils, namely Calcaric Fluvisols and Humic Podzols. Probability distributions of the land qualities workability and water deficit and of the physical suitability expressed as potato tuber yield were determined using a 30 years' record of weather data. Occurrence probabilities of workable days and water deficits are higher for the Humic Podzols, whereas for tuber yield the probabilities are higher for the Calcaric Fluvisols.

The mixed evaluation predominantly uses geographically referenced input data. Therefore, a linkage with geographical information systems is a prerequisite for an efficient use. When the data had been stored in a GIS, some recent projects showed that the mixed approach saved 50% to 70% time compared with the quantitative evaluation method having to be applied to all units.

INTRODUCTION

In the industrialized world, modern agriculture faces many problems. Recent environmental legislation, reduction in subsidies, and associated market regulations force farmers to change or adapt their production methods. The impact of alternatives on current agricultural practices, such as set-aside of land, low-input agricultural production systems, introduction of industrial crops, and short-rotation forestry, has to be investigated. Sensible land use adjustments cannot be made without evaluating the potentials and constraints of land (Bouma et al., 1986; Verheye, 1986; Dumanski et al., 1987; Lee, 1987; Bouma, 1989a). Land with its specific attributes, such as climate, topography, hydrology, and soil, is a crucial factor to be considered. Physical land evaluation can provide areal information on these potentials and constraints for a particular land utilization type in terms of crop yield and associated land qualities as far as affected by the physical environment.

There are different levels of detail in the technical approach of physical land evaluation, ranging from simple to detailed (Bouma, 1989a; 1989b). Each level can be defined in terms of the expected degree of detail of the results. Additionally, the required amount and detail of input data and the relative costs can be indicated. The levels are distinguished because appropriate input data for detailed analyses are lacking or because of the variety of questions being asked. Qualitative physical land evaluation methods, which represent less detailed technical approaches (e.g. farmers' experience, expert judgement) require fewer data and generally produce quick but broad answers (e.g. McKeague et al., 1984; Haans and Heide, 1984; Sys, 1985; Verheye, 1986; Lee, 1987). In an initial stage of problem analysis, qualitative methods can play a vital part (e.g. Van Lanen and Wopereis, in prep.). In later stages of evaluation, when land use exploration techniques are applied as proposed by De Wit et al. (1988), more quantitative information is needed. Input and output, such as nutrient and water requirements and expected crop yields of current and potential land utilization types, have to be quantified. Such information can be provided by quantitative physical land evaluation methods.

The essential difference between qualitative and quantitative procedures is that the quantitative ones comprise more detailed technical approaches. This implies the use of simple or complex dynamic computer models, simulating processes such as soil-water flow and crop growth. These methods render more specific results: land suitability, for instance, can be expressed in terms of occurrence probabilities of workable days or crop yields instead of broad expressions such as slight, moderate or severe limitations as provided by qualitative methods. In addition, quantitative methods are better fit to explore potential conditions, for instance possibilities for new crop varieties or the impact of a higher CO_2 concentration (e.g. Van Diepen et al., 1990). Quantitative evaluation methods, however, require more input data than the qualitative ones, so that they are generally more expensive. Therefore, we propose a combination of qualitative and quantitative methods for cases in which a quantitative evaluation is required.

The objectives of this paper are: (i) explaining the methodology of the mixed qualitative/quantitative physical land evaluation approach, (ii) illustrating the methodology, and (iii) analysing required efforts.

METHODOLOGY OF THE MIXED APPROACH

The mixed qualitative/quantitative physical land evaluation approach essentially consists of two components: (step 1) selecting potentially suited areas using qualitative procedures (Van Lanen et al., 1989), and (step 2) applying quantitative methods to the remaining potentially suited areas.

Qualitative land evaluation

After the land utilization type (LUT) to be considered has been defined, land is screened for obvious constraints through its specific attributes, such as soils, topography, hydrology, and climate (Fig. 1). Climatic requirements are defined first, based on expert knowledge, such as thermal regime, length of the growing season, and particular periods for certain field operations. The climatic requirements of the LUT, including the selected crop(s), are compared with the agro-climatic data of the area considered in order to exclude areas with unfavourable climatic conditions (Fig. 1, decision block 1). Next, other land use requirements must be defined that are essential for crop growth or farm management operations. These requirements include, for instance, specifications on soil texture, soil drainage, salinity, slope, and stoniness. Then, the mapping units that occur in areas without serious climatic limitations are screened for these land use requirements (Fig. 1, decision block 2). If a mapping unit does not meet the requirements, it will be excluded as less favoured land for that particular LUT. The remaining, potentially suited land has no severe limitations and will be subsequently analysed in more detail by quantitative methods.

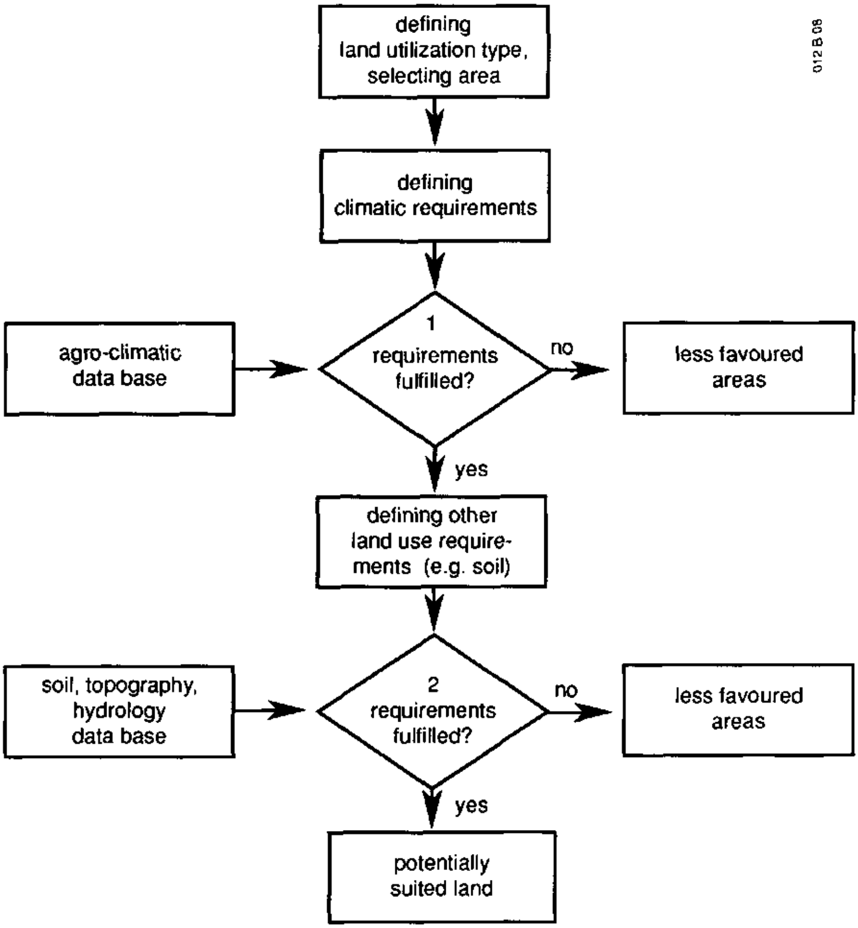


Fig. 1 Relational diagram to select potentially suited land.

For the definition of site requirements, the relatively limited availability of land data should be considered. If small-scale maps have to be used, either because detailed data are lacking or because large areas of land have to be investigated, the site requirements to be defined should fit with the usually broadly described attribute data (e.g. precipitation classes, soil texture classes) accompanying these maps.

Qualitative evaluation methods, based on expert knowledge, are expressly fit for the screening process. The screening for potentially suited land is in principle the same as the matching process, which is characteristic of the qualitative methods. Land use requirements are matched with land characteristics or land qualities to obtain the land suitability. Qualitative methods usually express the suitability in more than two classes, whereas the screening process determines two classes only, namely unsuited land and potentially suited land.

Qualitative evaluation methods have lately improved substantially by the development of systems for computer-captured expert knowledge. Especially the Automated Land Evaluation System (ALES), developed by Rossiter (1990), has comprehensive possibilities. ALES allows the land units to be screened quickly for the requirements to be met. Linkage of ALES with geographical information systems (GIS), in which digitized maps and attribute data have been stored, permits the quick production of maps showing the locations of potentially suited land. Moreover, tables providing areas of potentially suited land occurring in particular regions can be presented.

Quantitative land evaluation
After potentially suited land has been selected (step 1), quantitative evaluation methods are applied (step 2).

Schematic outline
Principal elements of the quantitative methods are dynamic, mechanistic computer models to simulate soil-water flow, evapotranspiration, and crop yield. Currently, many simulation models are operational and validated for a wide range of conditions (e.g. Bouma et al., 1980; Feddes et al., 1988; Dumanski and Onofrei, 1989; Ritchie and Crum, 1989; Van Diepen et al., 1989; Spitters et al., 1989). In the context of physical land evaluation, the technical approach in these dynamic simulation models can be classified as either simple or complex (Bouma, 1989a; 1989b). The simulation models can provide the user with quantitative data on land qualities (LQs), such as water deficit, soil aeration, and workability, and on the physical suitability expressed as crop yield. The quantitative evaluation procedure has been outlined in a relational diagram (Fig. 2) showing relations between soil and land characteristics (LCs), inferable soil and land characteristics (ILCs), LQs, and finally the physical land suitability. The term inferable characteristic has been introduced to replace the equivalent soil and land properties proposed by Bouma and Van Lanen (1987). The latter authors present a detailed description of the various parts of the diagram of Figure 2.

In the Netherlands many LCs, which are readily available from soil survey reports and geographical information systems, are used to evaluate land quantitatively. From these characteristics (lower part of Fig. 2) ILCs, such as bulk density, water retention ($\theta(h)$) and hydraulic conductivity ($K(h)$) curves, can be derived with pedotransfer functions (TF1 to TF4). On farm scale, use of soil structure type data in TF3 and TF4 allows $\theta(h)$ and $K(h)$ to be described more precisely (Van Lanen et al., 1987a). When reliable pedotransfer functions are available, deducing ILCs from basic soil survey information is a cheap alternative for measurements (Wösten et al., 1990). Water retention and hydraulic conductivity curves have to be obtained for every soil horizon. These data together with thickness of the horizon, rootable depth, mean highest water-table (MHW) and mean lowest water-table (MLW) are all input data for computer models simulating soil-water flow. In the Netherlands, the MHW and MLW are used for characterizing groundwater depths

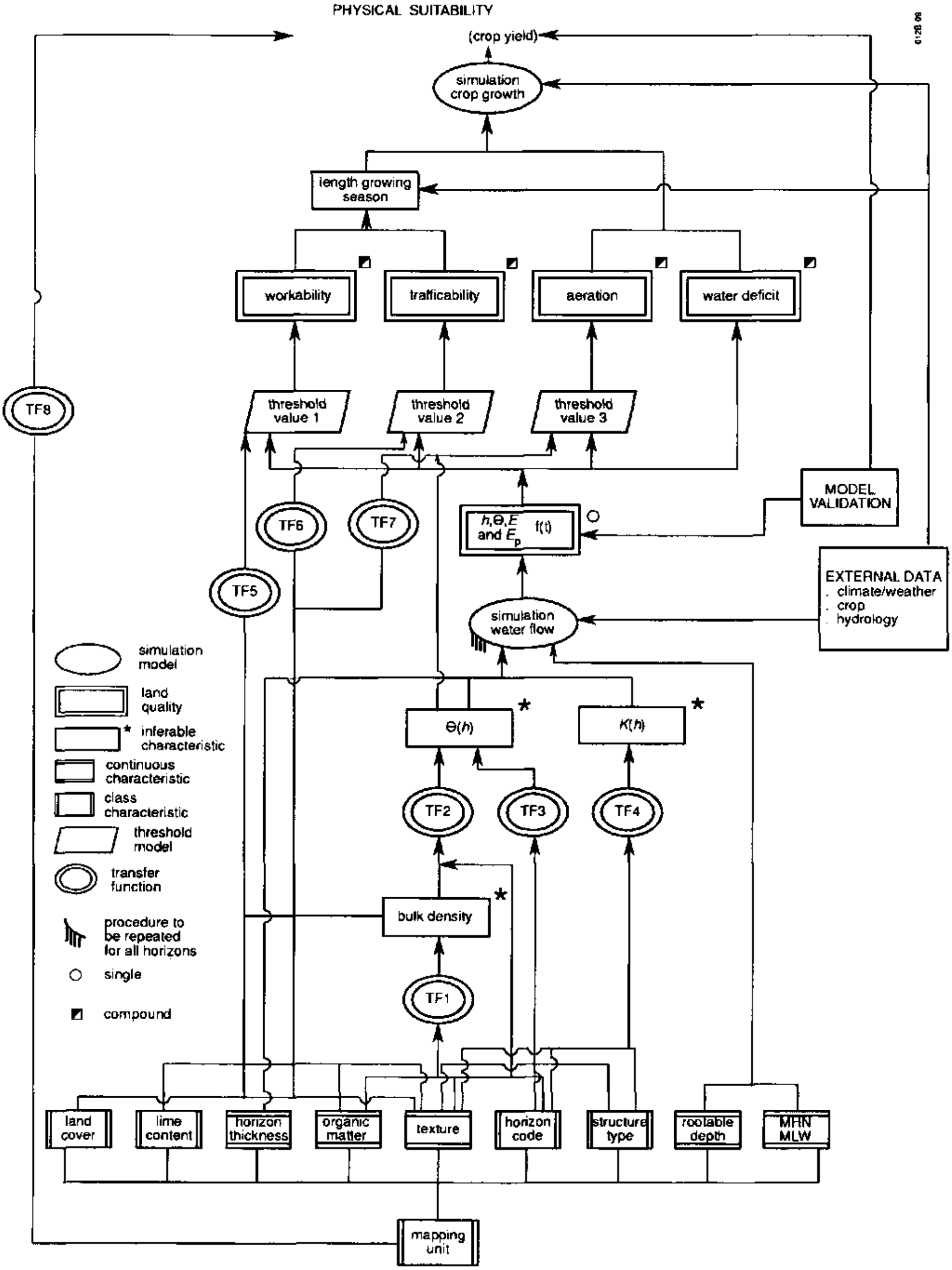


Fig. 2 General outline of the physical quantitative land evaluation approach.

(Van der Sluijs and De Gruijter, 1985). The models also need non-soil data, such as climatic, crop and hydrological information. In case of deep groundwater depths, fewer input data are needed. Usually information on MHW and MLW is not required and hydraulic conductivity data are only needed in comprehensive models.

Simple dynamic models

In simple dynamic models transient unsaturated water flow, as applied in our study, is usually approached by a sequence of pseudo-steady-state situations. Mostly the soil profile is subdivided into only two layers, to which the water budget approach is applied (e.g. De Laat, 1980). The models calculate actual and potential evapotranspirations (E and E_p), for instance for every ten days' period and for the entire growing season (e.g. Bouma et al., 1980). A water deficit occurs when E_p exceeds E. The water deficit is used as the main input for simple crop growth models (e.g. Van Lanen et al., 1987b), which compute relative crop yield (% of potential yield). Long-term average relative crop yield and probability distributions are calculated with historical records of weather data. In these models, adverse effects of water excess, such as inadequate workability and soil aeration, are not taken into account. Thus, threshold values 1 to 3 and LQs workability, trafficability and aeration (upper part of Fig. 2) are not used in a land evaluation with simple models.

In the simple models used in our study, processes associated with soil aeration, trafficability, workability and harvestability are represented elementary. In those cases in which water excess is relevant, the simulated relative water-limited crop yield is crudely corrected with a factor to account for a shorter growing season and inadequate soil aeration. The correction depends on MHW, MLW and soil texture (Werkgroep, 1987; Van Lanen et al., 1987b).

Complex dynamic models

In complex dynamic models, transient unsaturated water flow is usually approached by applying a finite difference technique to solve the combined Darcy flow and continuity equations (e.g. Feddes et al., 1988). The soil profile is subdivided into several layers with thicknesses of 5 to 10 cm. The models simulate E and E_p on a daily basis. The LQ water deficit for any period of time is defined as the difference between E and E_p. An essential difference with the simple models is the simulation of the pressure head h and water content θ for significantly more soil layers. The simulated daily pressure head profiles, especially for the plough layer, allow water-associated LQs, such as trafficability and workability to be determined. Simple threshold models are applied to convert h into these LQs. On every day of the simulated period, the simulated h of the topsoil is compared with threshold values 1 and 2 (upper part of Fig. 2). When h is below the threshold value, land is assumed to have an adequate trafficability or workability. When h is above the threshold value, land trafficability or workability is supposed to be inadequate (Van Wijk and Feddes, 1986; Van Lanen et al., 1987a). Threshold values for workability are determined by LCs soil texture, and organic-matter and lime contents (Fig. 2, TF5). Different threshold values for trafficability and workability have to be distinguished. The threshold value for trafficability is derived from land cover, soil texture, and bulk density (Fig. 2, TF6). The LQ soil aeration can also be determined by using a threshold model. Air-filled porosity can be used as an indicator of soil aeration. Air-filled porosity is calculated from total soil porosity and simulated θ and is then compared with a threshold value (Van Lanen et al., 1987a). This critical limit (Fig. 2, TF7) depends, amongst others things, on land cover, soil texture, and bulk density (Bakker et al., 1987). The threshold values for workability and trafficability also depend on the LUT (e.g. use of manpower, light or heavy machinery, crop type). Finally, the probability distributions of LQs water deficit, workability, trafficability, and soil aeration can be calculated by analysing a time series of simulated θ and h.

Van Wijk and Feddes (1986) outlined how threshold values for some LQs can be determined.

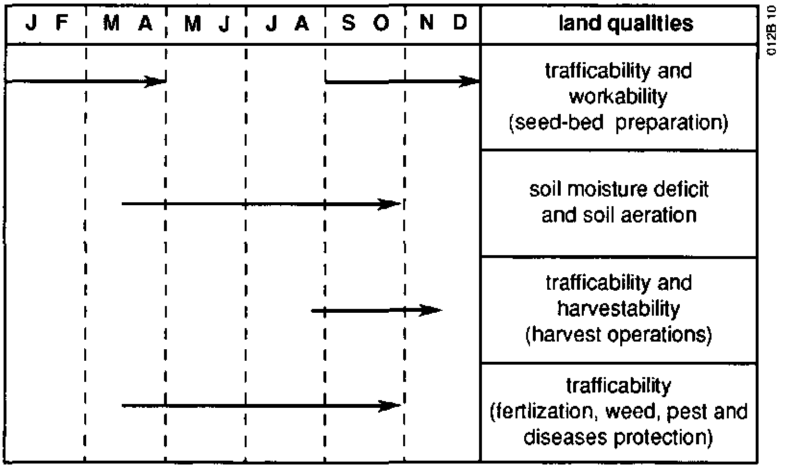


Fig. 3 Relevant periods of some land qualities for a spring-sown or planted crop under Western European climatic conditions.

Most LQs are only important for a particular period of a year. For a spring-sown crop under Western European conditions, these periods and LQs are presented in Figure 3. Trafficability and workability of the land determine when a spring crop can be sown or planted after a particular heat sum. In the period following sowing or planting, emergence starts. The length of emergence is derived from measured temperature and simulated pressure head (Van Wijk and Feddes, 1986; Hack-ten Broeke et al., 1989). After emergence, potential crop growth is supposed to take place as long as no soil-water deficit or inadequate soil aeration occurs. The potential crop growth is determined by meteorological conditions and crop processes, such as phenological development, light interception, assimilation, and respiration. Different complex crop growth models show different degrees of detail in which they treat these processes. When a water deficit or inadequate soil aeration occurs, crop growth will be reduced (e.g. Feddes et al., 1988; Van Diepen et al., 1989). Final crop yield is determined by either the crop maturity date or the harvestibility of the land when the crop matures late (Fig. 3). The LQ harvestibility is similar to trafficability or workability in the way it is assessed by applying threshold models.

Complex models incorporate more processes in the soil or crop, or they treat the processes more exhaustively than the simple models. In the simple models, part of the processes are represented by empirical relations, which only hold for a particular region or site conditions. Concepts of complex models are more comprehensive, but they generally require more data, more computer time, and more skilled users. In spite of the improved concepts of the complex models and the increasing computer power, simple models will be applied in land evaluation as well for a for some time for a number of reasons. In areas with shallow groundwater depths, the lower-boundary condition used in simple models as mentioned here, corresponds better with the land characteristics associated with groundwater depth, i.e. the MLW, than those currently incorporated in the complex models. Simple models use simple equations and straightforward numerical solution techniques without problems of numerical instability. Moreover, input and output handling of simple models is usually easy, which is extremely relevant in land evaluation because of the great number of mapping units to be evaluated.

APPLICATION OF THE MIXED APPROACH

In our study the mixed qualitative/quantitative approach is illustrated for potato-growing in the Netherlands. Potato is one of the products of an intensive crop rotation system with annual crops. Sufficient capital resources are available to buy first-quality seed potatoes as well as for optimal application of fertilizer and optimal control of weeds and diseases. Labour is scarce and, therefore, the mechanization degree is high. Land is conventionally tilled, which includes ploughing before preparing the planting bed. No supplementary irrigation is assumed to be applied and land is drained if necessary.

Qualitative land evaluation

Qualitative evaluation based on expert knowledge was used to screen the Netherlands for land with no serious restrictions for potato-growing. Existing expert knowledge (e.g. Van Loon, 1981; MacKerron, 1990) was converted into decision rules, which were integrated in ALES. In the Netherlands, no profound climatic restrictions would prevent potato-growing, so that the first part of the screening process (Fig. 1, decision block 1) could be omitted. Decision rules were formulated to screen the land for other land requirements, comparing them with LQs (Fig. 1, decision block 2) that can be derived from a soil map. The Soil Map of the Netherlands, scale 1 : 250 000 (Steur, 1985; Steur et al., 1986), which is stored in a geographical information system (GIS), was used. About 265 soil mapping units have been distinguished, distributed over the map in 6500 polygons. Land characteristics (LCs) have been provided for each mapping unit. Some LCs have been specified for all units, e.g. **groundwater depth class**, **presence of slopes**, and **flooding risk**. Other LCs are associated with the specific type of parent material, e.g. **soil texture of the topsoil** (mineral soils), **type of the topsoil** (peat soils), and **thickness of the topsoil** (sandy soils). Relevant LCs were combined into decision rules to define LQs. Soil-water supply capacity, soil drainage, terrain conditions (e.g. slopes), and soil-physical quality of the topsoil and the subsoil were distinguished as LQs. Soil-water supply capacity provides information on drought susceptibility. Soil-physical quality of the topsoil and soil drainage affect field trafficability, workability, and harvestability. As an example, a decision tree, which enables the screening of the soil mapping units for serious limitations considering the soil-water supply capacity, is presented in Figure 4. The LQ soil-water supply capacity was deduced by analysing the LCs parent material, groundwater class, texture of the topsoil, and thickness of topsoil. Finally, a simple decision tree was developed to combine straightforwardly the LQs used (Fig. 5) to identify soil mapping units potentially suited for potato-growing. Besides the above-mentioned LQs, the LC flooding risk was incorporated in the screening process. A maximum limitation method was applied, implying that if none of the LQs of a soil mapping unit has severe limitations, the unit is found to be potentially suited. More details on the use of expert knowledge to interrelate LCs and LQs in order to arrive at the physical suitability are presented by Rossiter (1990) and Van Lanen and Wopereis (in prep.).

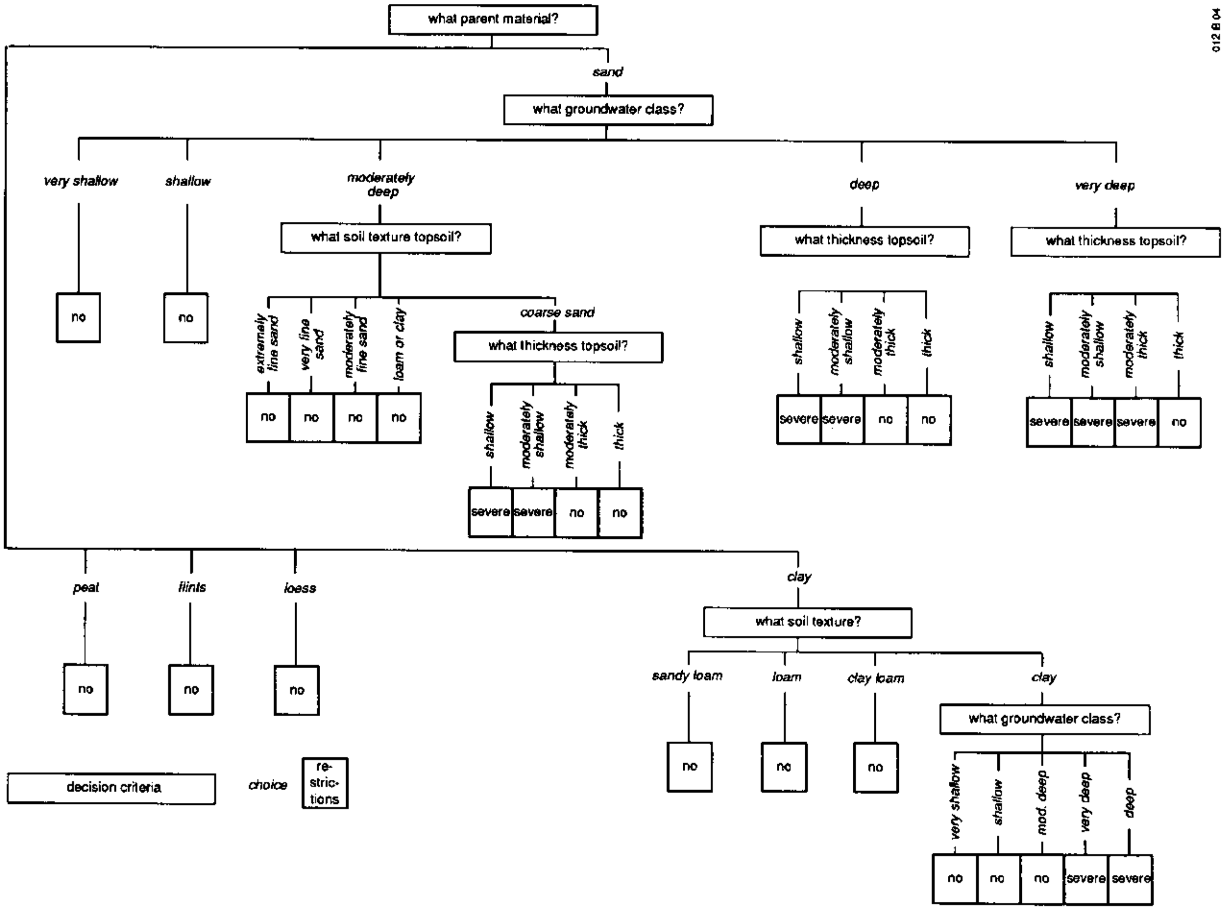


Fig. 4 Decision tree for the qualitative evaluation of land on limitations of the soil moisture capacity.

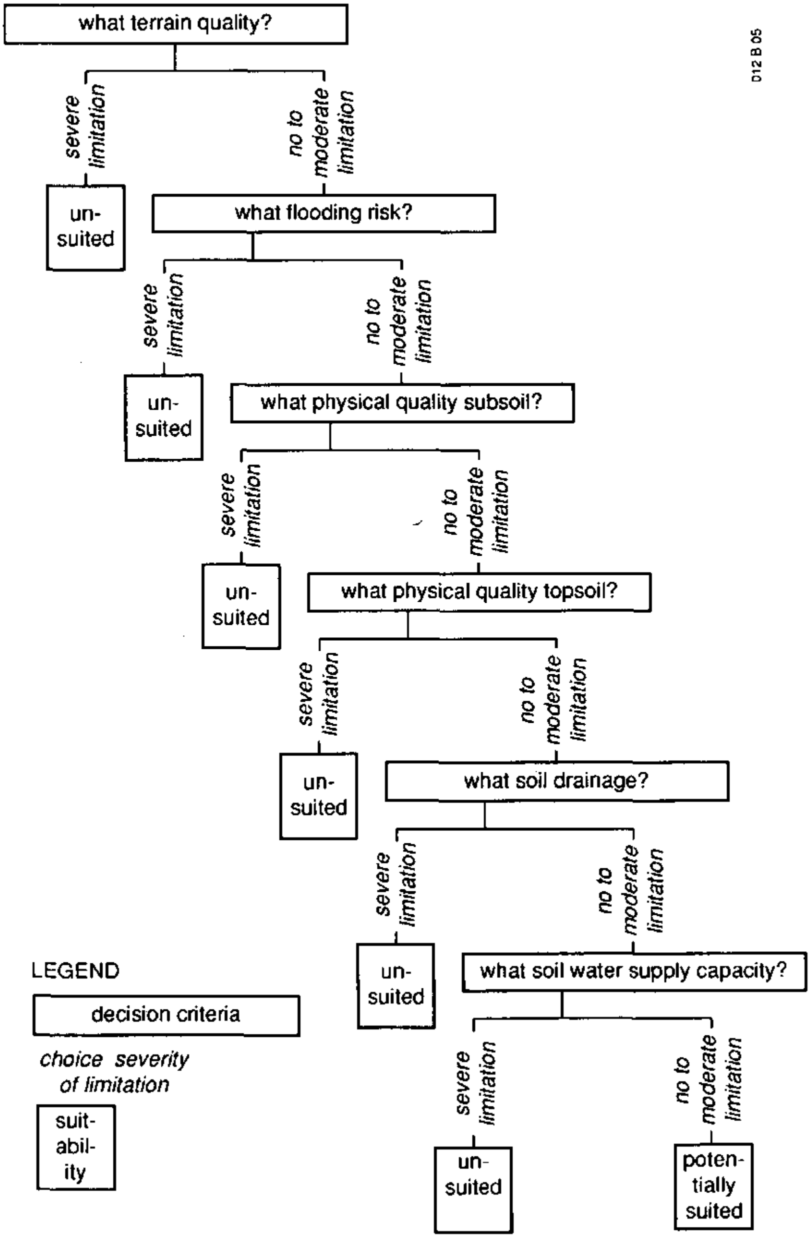


Fig. 5 Decision tree combining land qualities to screen land for potentially suitability for potato-growing.

Application of the qualitative method showed that about 65% of Dutch rural land is potentially suited to grow potatoes. Because of inadequate soil drainage and soil-physical quality of the topsoil, about 20% of the Dutch land is unsuited. A low soil-water supply capacity and a high flooding risk prevail on 10% and 5% of the land respectively.

Table I Relative areas (% of evaluated rural area) of potentially suited land for potato-growing in the CBS/LEI regions (see Fig. 6)

CBS/LEI region		Evaluated rural land (km^2) (%)	Potentially suited rural land
No.	Name		
1	Northern Clay	18 990	76
2	Holland and IJsselmeer Polders	21 140	85
3	Southwesterly Clay	31 190	87
4	River Clay	14 640	58
5	Loess	6 540	66
6	Northern Grassland	25 740	41
7	Western Grassland	36 440	30
8	Northern Sand	37 940	71
9	Eastern Sand	31 050	85
10	Central Sand	23 640	40
11	Southern Sand	52 890	73
12	Veenkoloniën	11 590	72
13	Rest of North Holland	5 810	62
14	Rest of South Holland	2 670	70
	Netherlands	32 027	65

Potentially suited land is distributed over the Netherlands as shown in Figure 6. Areas of potentially suited land for agro-statistical regions ('CBS/LEI regions') have been summarized in Table I. The results were obtained from an overlay of the map with the potentially suited areas (Fig. 6) and a map with CBS/LEI regions. In most regions, the percentage of potentially suited land is higher than 60%. The Western Grassland and Northern Grassland regions have low percentages of suited land, namely 30% and 41% respectively. Inadequate soil drainage and physical quality of the topsoil are the major restrictions in these regions, whereas in the Central Sand region an extremely low moisture supply capacity prevails (40% of the land is potentially suited in this region). In the other sandy regions, relatively high percentages of potentially suited land occur (71% to 85%), although moderate constraints for growing potatoes can be expected.

When it is uncertain whether a land unit with a compound soil texture or groundwater depth class is unsuited or potentially suited (Van Lanen and Wopereis, in prep.), it has to be evaluated as potentially suited. Land with profound constraints is not considered in the quantitative evaluation. Hence, a broadly defined unit, characteristic of small-scale maps, will sooner be regarded as potentially suited than the more precise units of larger scaled maps. Therefore, the area of potentially suited land also depends on the map scale and attribute data. Van Lanen et al. (1989) showed that use of the Soil Map of the European Communities, scale 1 : 1 000 000 (Commission, 1985), results in about 80% of Dutch land being regarded as potentially suited for potato-growing.

The conclusion of this study, which uses the Soil Map of the Netherlands, scale 1 : 250 000, is that only 65% of the land is potentially suited for potato-growing.

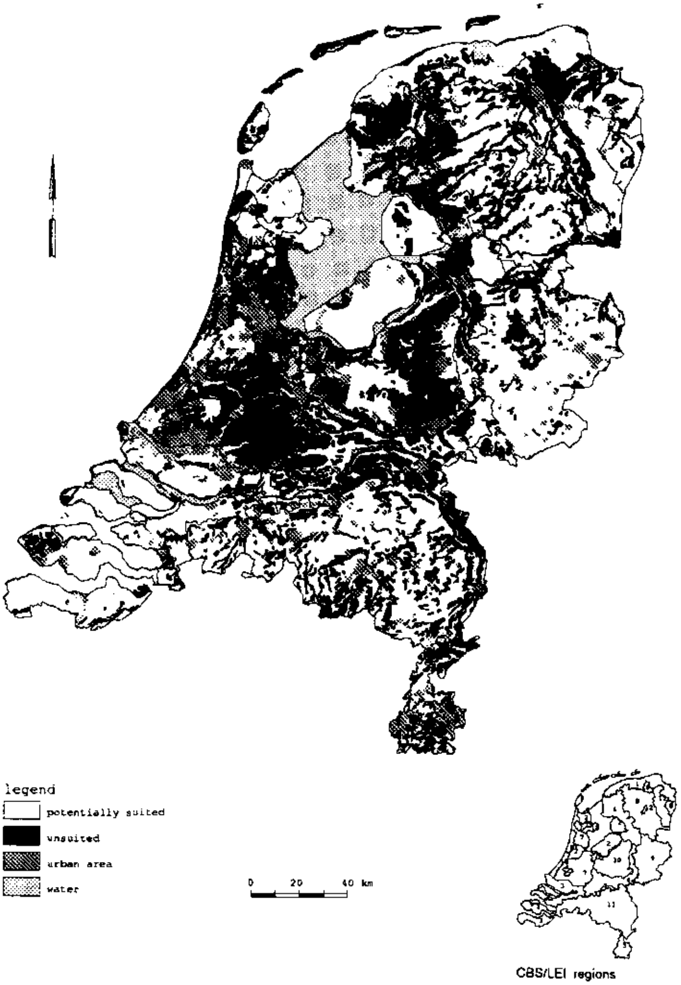


Fig. 6 Potentially suited land for potato-growing in the Netherlands.

Quantitative land evaluation
On a more detailed scale, quantitative evaluation models were applied to a few areas having relatively large areas of potentially suited land for potato-growing according to the qualitative evaluation in the previous step. First, the results of simple models will be presented, and then those of more complex models will be dealt with.

Simple dynamic models

Simple quantitative evaluation models were applied to the sandy area of Bornerbroekse Waterleiding (630 ha) located in the eastern part of the Netherlands. The Regge en Dinkel Water Board wanted to know if crop yield in this area could be improved by drainage (De Groot et al., 1989). Humic Gleysols (Food, 1974), also classified as Typic Humaquepts (Soil, 1975), with a loamy sand texture and mostly with a clayey topsoil are the principal soils in the area. Another important group is formed by the Gleyic Podzols (Typic Haplaquods), the texture of which ranges from sand to loamy sand. About 60% of the area has a mean highest water-table (MHW) deeper than 40 cm below surface. The mean lowest water-table (MLW) is between 100 and 200 cm below surface in almost the entire area. About half of the area has an MLW between 100 and 150 cm. For a more comprehensive description of the mapping units the reader is referred to Ebbers and Visschers (1983).

Although the sandy soils of Bornerbroekse Waterleiding were not expected to be the best possible land for potatoes, the qualitative land evaluation, applied in the previous step, yielded a relatively large area (about 90%) of potentially suited land. Therefore, the region was subsequently evaluated by quantitative methods. For each mapping unit of the soil map, scale 1 : 50 000 (Ebbers and Visschers; 1983), the physical suitability was determined, expressed in terms of relative crop yield. A pedotransfer function (Fig. 2, TF8) was used to assess the suitability. This class pedotransfer function had been established by running the simple soil-water flow and crop growth models for a wide range of combinations of soil types, MHWs and MLWs (Werkgroep, 1987). This time-consuming effort was carried out by the Government Service of Land and Water Use to prevent the models from being repeatedly run for every rural development plan and to avoid their being applied by unskilled users. After the mapping units of the soil map, scale 1 : 50 000, had been converted into soil types incorporated in the pedotransfer function, the relative potato yield was easily obtained (De Groot et al., 1989).

The average relative yield depressions for potatoes for the units in the area of Bornerbroekse Waterleiding vary from less than 5% to more than 25% (Fig. 7). The relative yield depression is expressed as a percentage of the potential yield. In the results presented, only the effect of drought stress was taken into account. Half of the area has a low long-term average yield depression (< 5%). A yield depression of more than 10% may be expected in 25% of the area, and a depression of 20% or more would occur in about 5% of the area. Actually, mapping units with an average depression of more than 20% should have been evaluated as unsuited land and should therefore have been excluded by the qualitative methods. These mapping units, however, are not explicitly represented on the small-scale soil map that is used for the screening, because their areas are too small.

Mapping units with shallow groundwater depths usually have a low yield depression when only drought stress is considered. But the yield will be affected by inadequate trafficability, workability, and aeration. Applying the crude rules provided by the Werkgroep Help-tabel (1987) showed that about 40% of the area would have a yield depression of more than 10% due to water excess. Thus, nearly all the mapping units in Bornerbroekse Waterleiding would have a yield depressions of more than 10%, either because of drought stress or because of water excess. When both drought stress and water excess are accounted for, less than 15% of the area has an average yield depression of less than 10%. This area with a depression less than 10% can be considered as well suited for potato-growing.

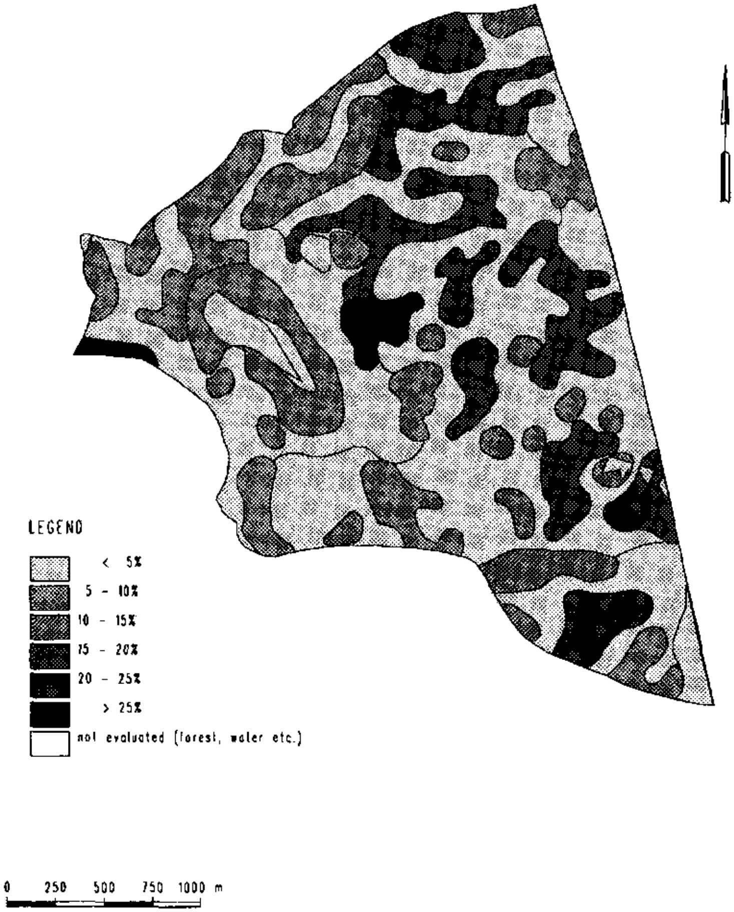


Fig. 7 Simulated average relative yield depression (% of potential yield) for potatoes in a Dutch sandy area owing to drought stress.

Complex dynamic models

Applicability of complex dynamic simulation models to quantitative evaluation will be illustrated with the results of two Dutch areas with contrasting soil mapping units (Hack-ten Broeke et al., 1989). The dominant unit in one area belongs to potentially suited land for potato-growing and is located in the IJsselmeer Polder (Research Station for Arable Farming and Field Production of Vegetables, Lelystad). The relatively young marine soils of this unit are classified as Calcaric Fluvisols (Food, 1974) or Typic Fluvaquents (Soil, 1975). These soils have a topsoil of loam to clay loam and a sandy loam subsoil, and they are well drained; the MHW is between 60 and 70 cm and the MLW between 140 and 180 cm below soil surface. The mapping unit covers about 100 000 ha in the Netherlands. In the other area, mapping units occur that were found to be potentially suited for potato-growing, although the potato yield was expected to be affected by a moderately low soil-water supply capacity. The man-made or anthropic topsoil of the unit consists of allochthonous material (< 50 cm), gradually added by man in the practice of using earth-containing manure. The soils of this unit are located in the central part of the Netherlands (Sinderhoeve Experimental Station, Renkum) and have been developed in sandy, fluvioglacial, mostly gravelly sediments. They are classified as Humic Podzols and Plaggeptic Haplohumods, in accordance with Food (1974) and Soil (1975) respectively. Groundwater is deeper than 10 m below soil surface. The mapping unit covers about 10 000 ha in the Netherlands. More details on these two mapping units have been provided by Van Lanen and Van Soesbergen (1990).

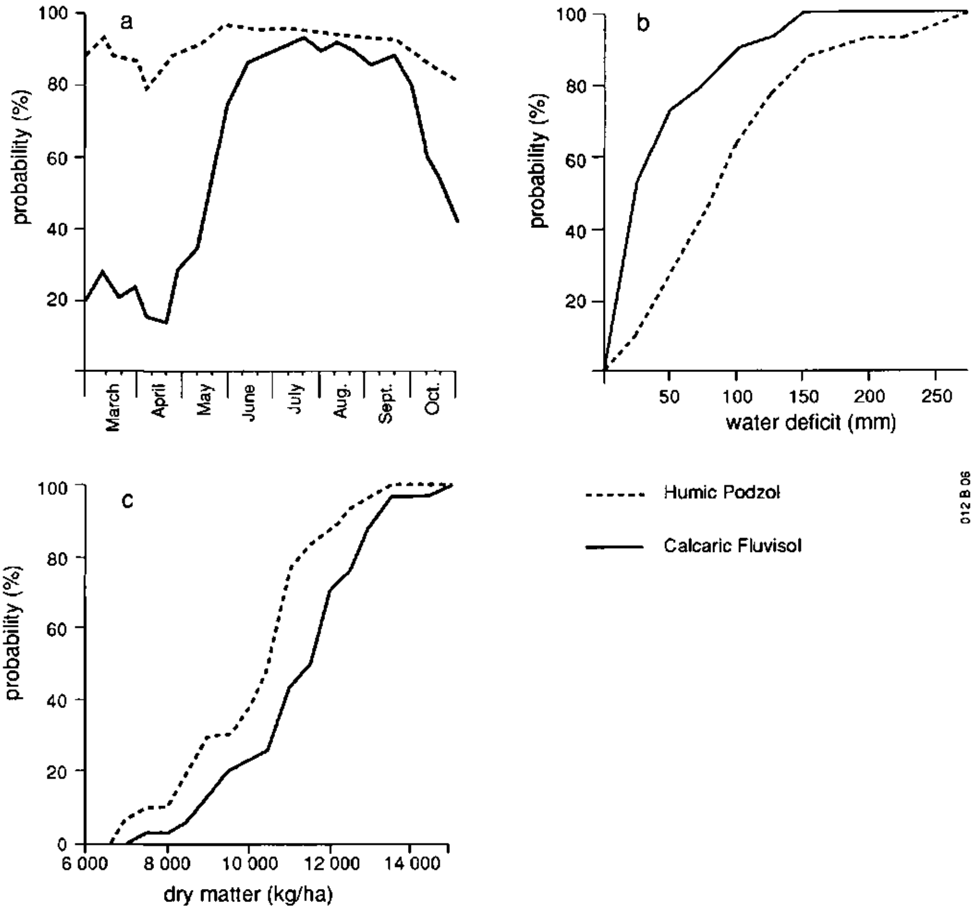


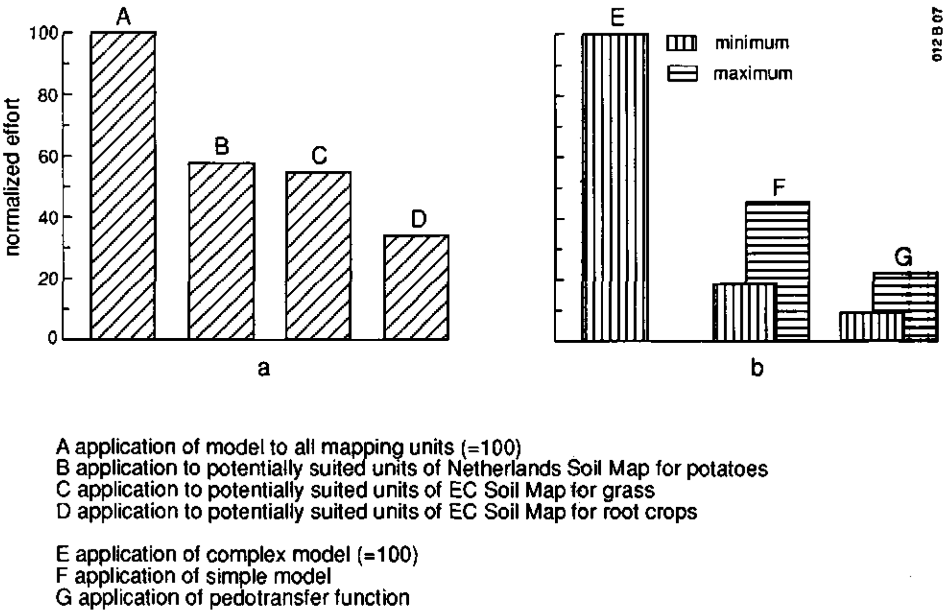
Fig. 8 Occurrence probabilities of two land qualities and of crop yield for two contrasting Dutch soil mapping units; (a) median of workable days, (b) water deficits (total growing season), and (c) potato tuber yield.

After validating the SWANY model (Hack-ten Broeke et al., 1990), which was derived from the SWACROP model (Feddes et al., 1988), occurrence probabilities of the LQs water deficit and workability and of the potato yield were determined for both mapping units (Fig. 8). Probability distributions were based on an analysis of simulated evapotranspiration, pressure heads, and potato tuber yields covering a period of 30 years.

Under Dutch climatic circumstances, the number of workable days on the Calcaric Fluvisol is significantly lower than that on the Humic Podzol (Fig. 8a). For instance, in the planting period (March 15 to April 30), in 50% of the years no more than two or three days in a ten days' period will have an adequate workability on the Calcaric Fluvisol, whereas on the Humic Podzol more than eight days in a ten days' period will be available. Thus, planting and emergence dates will be earlier on the Humic Podzol than on the Calcaric Fluvisol, allowing a longer growing season (Hack-ten Broeke et al., 1989).

In 50 out of 100 years potatoes grown on the Calcaric Fluvisol will have a water deficit of less than 20 mm, but on the Humic Podzol the deficit will be up to 80 mm (Fig. 8b). In 10 out of 100 years the deficit will exceed 90 mm on the Calcaric Fluvisol and 160 mm on the Humic Podzol. The higher drought susceptibility of the Humic Podzol will certainly affect crop growth.

In 30 out of 100 years potato tuber yield (dry matter) will be less than 9000 kg ha^{-1} on the Humic Podzol, whereas on the Calcaric Fluvisol the yield will be up to 11 500 kg ha^{-1} (Fig. 8c). In only 25 out of 100 years the tuber yield on the Humic Podzol will be higher than 11 000 kg ha^{-1}, whereas on the Calcaric Fluvisol the yield will then exceed 12 500 kg ha^{-1}. These yields are attainable, as has been shown at experimental farms (Hack-ten Broeke et al., 1990).



A application of model to all mapping units (=100)
B application to potentially suited units of Netherlands Soil Map for potatoes
C application to potentially suited units of EC Soil Map for grass
D application to potentially suited units of EC Soil Map for root crops

E application of complex model (=100)
F application of simple model
G application of pedotransfer function

Fig. 9 **Rough estimate of differences between normalized efforts required for different land evaluation approaches; (a) effort needed when only potentially suited mapping units are evaluated as compared with an evaluation of all units, and (b) range of efforts needed when simple models or pedotransfer functions are applied as compared with complex models.**

Estimated efforts for application of the mixed approach

When quantitative methods have to be applied, the proposed mixed qualitative/quantitative approach prevents useless, time-consuming application of comprehensive tools to land with obvious limitations for a particular land use option. Time was saved substantially by using the mixed approach in a study on assessing the crop production potential of the European Communities (Van Lanen et al., in prep.). Little effort was needed to screen land for its suitability for major crops. Applying the time-consuming model simulating soil-water balance and crop growth to all the mapping units would take twice or thrice as much time as applying it to the potentially suited units only (Fig. 9a). The same holds for evaluating the potato yield by computer models using the Soil Map of the Netherlands, scale 1 : 250 000 (Fig. 9a). Map scale, crop type (e.g. less or more demanding) and natural resources themselves (e.g. many units with first-class land versus many units with unsuited land) affect the amount of time required. Experiences from some recent land evaluation projects indicate that use of complex models requires two to five times as much time as use of simple models (Fig. 9b). A recent project showed that applying the above-mentioned pedotransfer function instead of running the simple models themselves saved approximately 50% of time (Fig. 9b). Estimated efforts, as presented in Figure 9, are normalized, but of course depend on the type of model, the type of pedotransfer function, and on the number of mapping units. Moreover, Figure 9 holds for the situation that the data have been stored in a GIS, no soil-hydraulic or crop properties have to be measured, and the models have already been validated. When soil and climate data must be gathered from reports, properties have to be measured, or an extensive validation of the computer models is required, the relative differences between the approaches (Fig. 9) will be small compared to these efforts.

DISCUSSION AND CONCLUSIONS

Policy-making on the subject of sustainable land use and rural development should be an interactive process, which requires flexible analysis tools. Use of the mixed qualitative/quantitative physical land evaluation approach elaborated in our study, together with complementary tools, such as geographical information systems (GIS), can significantly improve flexibility.

A similar approach, as proposed in our study, is being elaborated in Canada, where agro-ecological resource areas on a scale of 1 : 2 000 000 are distinguished presenting broad biophysical potentials and constraints relevant to agricultural issues (Pettapiece and Hiley, 1989). Subsequent analysis focuses on promising areas, viz. the prairie region (e.g. Dumanski and Onofrei, 1989).

Our study showed that qualitative evaluation methods, as first step of the mixed approach, can quickly screen relatively large areas of land for broad biophysical potentials considering specified land use options. A prerequisite for a fast analysis, however, is that biophysical data have been stored in a GIS. Furthermore, expert knowledge, characteristic of qualitative evaluation models, must preferably be captured in a computer system using processing tools such as ALES (Rossiter, 1990). The area of potentially suited land was found to depend on the map scale and associated attribute data. Use of larger scaled maps will usually render a more precise estimate of the potentially suited area. The area to be screened for potentially suited land, together with the required reliability and available resources, will determine which map scale is optimal.

The application of quantitative methods, based on computer simulation, as second step of the mixed approach provides more specific results for the remaining, potentially suited land. The objectives of the study determine whether simple or complex computer models must be applied. In some cases, when the simple models have to be run for many soil mapping units, pedotransfer functions can be used, as is illustrated in this study for potentials of potato-growing in the Netherlands. The pedotransfer function, however, does not produce reliable results for specific soil conditions, because they were not taken into consideration when deriving the functions.

Results of simple models are less specific than complex-model results. Reliable probability distributions of land qualities such as workability cannot be supplied by simple models, because they are unable to simulate soil moisture-conditions in the plough layer accurately enough. Probability distributions of LQs and crop yield are needed for risk analysis (e.g. Dumanski and Onofrei, 1989; Thornton and Dent, 1990). Furthermore, without an extensive calibration of region- or environment-specific parameters, the applicability of simple models is generally restricted. Complex models have a greater transferability, but usually data, computer and staff requirements are higher.

In case a quantitative evaluation has to be conducted, use of a mixed qualitative/quantitative approach can substantially save time. Analysis of some recent projects showed that a reduction in efforts by 50% to 70% could be attained.

ACKNOWLEDGEMENTS

The authors wish to thank Rini Schuiling and Hans de Wijer for applying the ARC/INFO software. The first author wants to express his appreciation for the stimulating discussions with Dr. Julian Dumanski and Dr. Constatin Onofrei during his visit to the Land Resource Research Centre, Canada, in 1989.

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7 PHYSICAL LAND EVALUATION METHODS AND GIS TO EXPLORE THE CROP GROWTH POTENTIAL AND ITS EFFECTS WITHIN THE EUROPEAN COMMUNITIES

Submitted for publication in Agricultural Systems

Physical Land Evaluation Methods and GIS to Explore the Crop Growth Potential and its Effects within the European Communities

H.A.J. VAN LANEN, C.A. VAN DIEPEN, G.J. REINDS, G.H.J. DE KONING, J.D. BULENS & A.K. BREGT

The Winand Staring Centre for Integrated Land, Soil and
Water Research, P.O. Box 125, 6700 AC Wageningen
(the Netherlands)

ABSTRACT

Qualitative and quantitative physical land evaluation methods were developed and linked with a geographical information system (GIS) to evaluate crop growth potential in the European Communities (EC). Evaluation methods comprised expert knowledge and crop growth modelling. The predicted crop growth potential is primarily meant for exploring land use options. In this paper, the wheat crop is used to illustrate the methodology. All potentially suited land units were identified first using computer-captured expert knowledge, followed by calculating the potential and water-limited yields on these land units with a simulation model. Land unsuited for wheat-growing amounts up to 55% of the EC area and is mainly concentrated in the Mediterranean countries. Without increasing the EC wheat area, the wheat production volume can still substantially increase by 65% under water-limited and 120% under potential production conditions. Results obtained were used to quantify the impact of set-aside of either highly productive land or marginal land on production reduction. In many EC regions marginal land used for wheat-growing produces at least 50% less than highly productive land. The production potential should be incorporated in set-aside measures to be imposed.

INTRODUCTION

In many areas within the European Communities (EC) a structural transformation of the agricultural sector has occurred in the past 25 years. In favourable agricultural regions the farm size increased, land parcels were consolidated, narrow crop rotations were introduced, and farmers specialized in either crop or animal production. Support offered by the Common Agricultural Policy (CAP) and technological innovations eventually resulted in surpluses of, for instance, milk, cereals and sugar. The availability of relatively inexpensive agro-chemicals and feedstuffs substantially contributed to the intensification of agriculture. These developments, however, had a major impact on environment, nature and landscape (Briggs and Wilson, 1987). Now, many of the intensively cultivated areas suffer from groundwater pollution and soil degradation (e.g erosion, saturation of soils with agro-chemicals). In other areas, less-favoured for agriculture, abandonment and associated social hardship occurs.

EC budgets are increasingly called upon to mitigate undesirable socio-economic and environmental effects of the CAP. Plant and animal production per unit area are likely to continue their increase as postulated by De Wit et al. (1987) if no specific measures are issued. All these developments force policy-makers to reorient the CAP to economic efficiency, social equity, and ecological stability. Although perspectives for an adapted Common Agricultural Policy have been proposed for years (Commission, 1985a; De Wit et al., 1987; Conrad, 1987), we are still insufficiently aware of the impact of EC structural measures on land use and associated rural development. Therefore, the Dutch Scientific Council for Government Policy (WRR) develops a model for general optimal allocation of land use to explore possible regional land use options within the EC.

The WRR model incorporates aspects such as agro-technics, socio-economics, environment, nature, landscape, and physical planning (Van Latesteijn, 1990). A quantitative assessment of agro-technical data is needed, such as regional yields, areas and associated inputs (e.g. nutrients, water) of various crops. These data should not only apply to the actual situation in the EC, but also to the agro-ecological potential which can be explored by defining biologically attainable production levels. Currently, no appropriate data are available for these attainable situations. Existing data either cover only part of the EC or are restricted to one particular production level (e.g. Buringh et al., 1979; Verheije, 1986; Lee, 1986; 1987; Van Lanen and Bregt, 1989). Therefore, an agro-ecological analysis of the EC, consisting of an evaluation of soils, climate and crops, was carried out to examine regional crop yield for several attainable production situations. Qualitative and quantitative physical land evaluation models, comprising expert knowledge and crop growth modelling, were developed and linked to a geographical information system (GIS). The results of this combined approach are not primarily intended for predicting real-time crop yields. Instead, they are meant to explore the impact of the crop growth potential on land use options.

The objective of this contribution is (i) to explain the developed methodology, which combines physical land evaluation methods and GIS; (ii) to present some results on regional EC wheat growth potential and its effects showing the applicability of the methodology developed.

MATERIALS

Knowledge of the geographical distributions of soil, climate and administrative units and their associated attribute data is essential to explore regional crop growth potential. Furthermore, crop characteristics are needed to define particular crops. As maps and attribute data have to cover the whole EC, only small-scale maps and associated data bases were used.

Soil data

The geographical distribution of soils throughout the EC was derived from the EC Soil Map, scale 1 : 1 000 000 (Commission, 1985b). Including soil phases, 546 soil associations have been distinguished, distributed over more than 15 000 delineations. Each soil association contains a dominant soil unit, associated units, and inclusions. The available soil attribute data restricted the evaluation to the dominant soil units. These units cover slightly over 60% of the EC area. Probably, the results apply to a larger area, because associated units and inclusions of a soil association can have the same characteristics relevant to crop growth assessment as the dominant unit. The dominant soil unit usually has a compound soil texture and/or slope. Therefore, single subunits with uniform texture classes were distinguished, assuming an equal areal distribution of texture classes within the compound dominant soil unit. Land characteristics of the dominant soil unit are either provided by the map legend (e.g. soil texture and slope class), or were derived by an interpretation procedure (e.g. drainage class, rootable depth). For instance, the drainage class was deduced from the pedogenetic name, which is based on hydromorphic features in the soil profile, in combination with the soil texture. Furthermore, water retention data were allocated to the unit taking into account soil texture. More details on the interpretation procedure are provided by Reinds et al. (in press).

Agro-climatic data

An agro-climatic map was compiled based upon the Agro-climatic Atlas of Europe (Thran and Broekhuizen, 1965). One hundred and nine agro-climatic zones were distinguished. A representative meteorological station was allocated to each zone, assuming no climatological gradients within the zone. In mountainous areas a station representative of valley conditions was chosen, because major agricultural activities are assumed to be concentrated there. Year to year weather variation was considered by using a 26 years' historical record of monthly data. The data set comprises minimum temperature, maximum temperature, global radiation, wind speed, vapour pressure, rainfall, and number of rainy days. Daily rainfall was stochastically generated using monthly rainfall and number of rainy days. Other daily weather data were obtained by linear interpolation. No historical data records were available of about 20% of the stations. In these cases, long-term mean monthly weather data were used (e.g. Müller, 1987; Wallén, 1977).

Administrative EC regions

The subdivision of the EC into 64 administrative regions at the so-called NUTS-1 (Nomenclature of Territorial Units for Statistics) level was used. A NUTS-1 region coincides with one or more provinces or districts within a country. Eurostat (e.g. Eurostat, 1987) provides data on current areas, production and yield of various crops within the NUTS-1 regions. Reference to administrative regions allows basic data (e.g. soil) and physical land evaluation results (e.g. crop yield) to be aggregated to NUTS-1 level. Then, calculated data can be compared with statistical data.

Crop characteristics

The crop data requirements depend on the procedure for which they are needed. Climatic and edaphic requirements, e.g. soil drainage and soil salinity, must be known for selecting land suited for the cultivation. Moreover, crop-specific properties such as physiological and phenological crop parameters required by the crop growth model were gathered, e.g. initial biomass, life span of the leaves, death rates, and fractions of the assimilates partitioned to plant organs. Crop model parameters for winter wheat were derived from Spitters et al. (1989). Most parameters are universally valid, but some depend on environment and cultivar. Therefore, region-specific information was gathered on the cropping calendar, such as sowing or planting dates, for use as model input, and on dates of flowering and maturity for adjusting the model to local conditions.

METHODS

Qualitative and quantitative physical land evaluation methods were developed and linked with a GIS to explore the crop growth potential and to examine its effect. The general outline of the methodology is illustrated in Fig. 1.

GIS

A partial linkage of the GIS and the physical land evaluation methods was used (Bregt et al., 1989; Bulens et al., 1990). The GIS, developed for this study, supplied input data for the land evaluation models and accepted modelling results for further processing and presentation. Three digitized maps, comprising the geographical distributions of soils, agro-climate, and

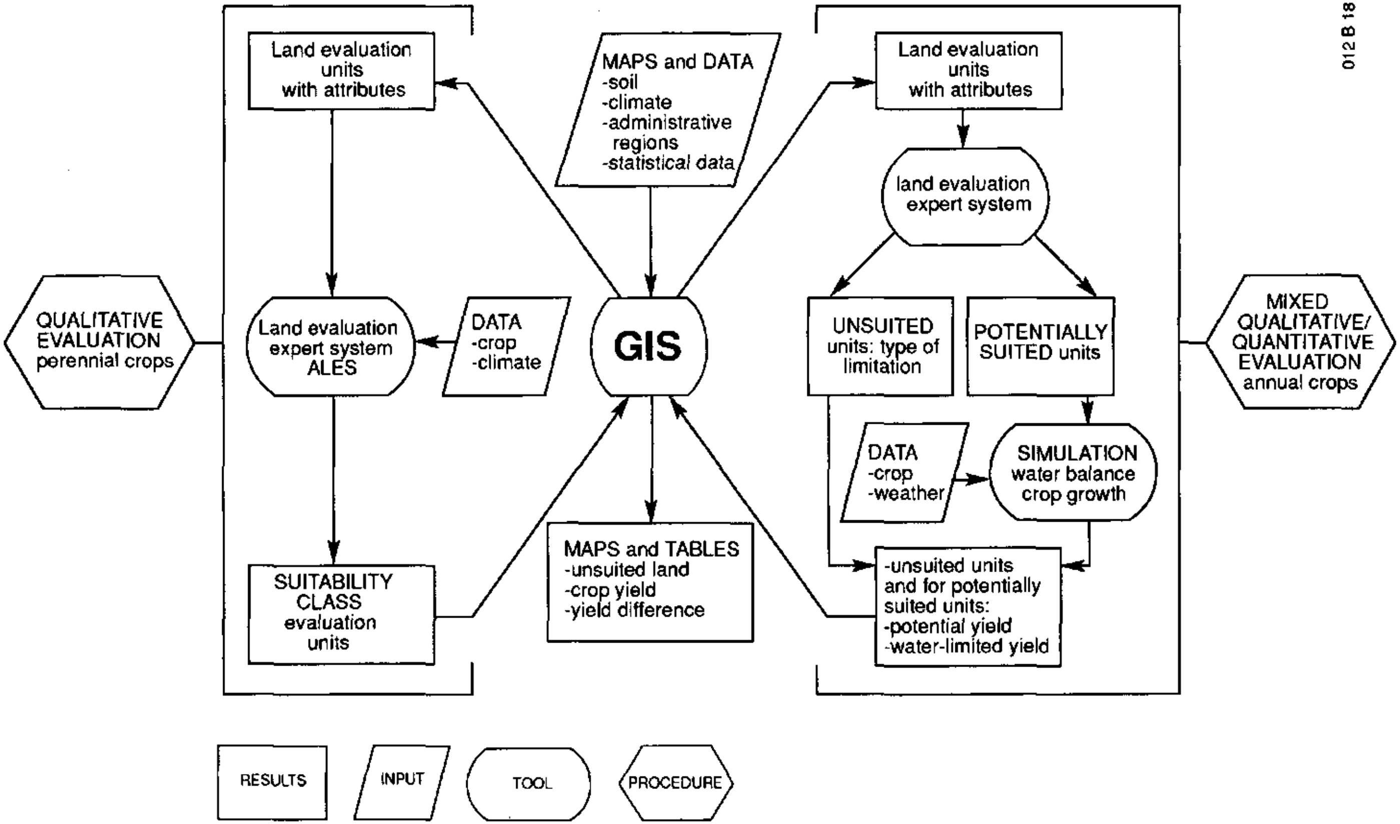

Fig. 1 Outline of the land evaluation procedure.

administrative regions (NUTS-1 level), were stored in the GIS together with attribute data (e.g. soil texture, actual wheat yield). A map overlay was carried out using ARC/INFO software, which resulted in a map with land evaluation units (LEUs). Each LEU is a unique combination of a soil unit, an agro-climatic zone, and a NUTS-1 region. About 4200 LEUs were distinguished, distributed over more than 22 000 polygons. The physical land evaluation methods were applied to each of these LEUs and the results were subsequently stored in the GIS. Results were presented as tables and maps using the ARC/INFO software package. The weighted mean areas and yields of geographical units can be computed by the GIS, using calculated yields and the areas of LEUs which occur in the geographical unit. This spatial aggregation was carried out for the agro-climatic zones, NUTS-1 regions, member states, and the entire EC.

Qualitative land evaluation method

Qualitative physical land evaluation methods indicate the degree of suitability of land for a particular land use in a descriptive way (e.g. well suited, marginally suited). The principles have been outlined by the FAO (Food, 1976).

Qualitative methods were used when insufficient crop data for a quantitative land evaluation procedure were lacking. Therefore, qualitative methods were applied to forestry and fruit species such as apples, peaches, olives, citrus and grapes.

Use of expert knowledge is characteristic for qualitative methods. Decision rules were captured in a computer system using ALES (Rossiter, 1990). Qualitative methods yield regional areas of well suited, moderately suited and unsuited land (Fig. 1, left part). These methods do, however, not predict crop yields associated with the suitability classes. Yield data for the diverse production situations have to be allocated to these classes by analysing results of experimental fields or statistical data. Results of the qualitative methods are discussed elsewhere (Van Lanen et al., in prep.), as this contribution is restricted to the growth potential of wheat.

A mixed qualitative/quantitative physical land evaluation procedure (Fig. 1, right part) as proposed by Van Lanen et al. (1989) was developed for some annual reference crops, such as wheat (Reinds & Van Lanen, in press). In the mixed approach, qualitative evaluation methods are used as a first step to screen the LEUs for crop- and management-specific requirements. LEUs are considered unsuited when they do not meet these requirements. To the remaining, potentially suited LEUs the quantitative evaluation methods are applied. We considered LEUs potentially suited for wheat-growing at mechanized farms under the following conditions: (1) soils with less than 60% clay, (2) land having a slope less than 15%, (3) soils at least moderately well drained, (4) a rooting depth of more than 10 cm, (5) no excessive salinity or alkalinity, and (6) no soil phase other than gravelly or concretionary. These decision rules were captured in a computer using ALES and subsequently all LEUs were automatically screened, resulting in a list of potentially suited LEUs and areas of potentially suited land.

The mixed qualitative/quantitative evaluation procedure was not only applied to wheat, but also to sugar-beets, potatoes, maize, oil-seed rape, and intensively managed grassland (De Koning et al., in press a).

Quantitative land evaluation method

Quantitative physical land evaluation methods yield quantitative expressions for crop production, such as crop yield in kg dry matter per unit of area, and associated inputs (e.g. m^3 water, kg nutrients). Computer models simulating soil water flow and associated crop growth and production are essential parts (e.g. Bouma, 1989; Van Diepen et al., 1991). The quantitative method was applied to the potentially suited LEUs preselected with qualitative land evaluation methods (Fig. 1, right part).

The WOFOST model, as described by Van Keulen and Wolf (1986) and Van Diepen et al. (1989) and validated by, amongst others, De Koning et al. (in press b), formed an essential part of the quantitative land evaluation method. WOFOST simulates the growth and production of a crop and the soil-water balance in daily time steps under prevailing weather and site conditions. WOFOST was adapted to allow sowing or planting dates in the northern member states to be simulated. The major simulated processes in the crop submodel are phenological development, light interception, assimilation, respiration, partition of dry-matter increase over plant organs, and transpiration.

Crop yields were calculated for two attainable production situations: potential and water-limited. The potential crop yield is the integrated expression of the influence of sunlight and temperature on the growth of a particular crop cultivar. The potential crop yield can be interpreted as the upper yield limit, when only radiation and temperature are considered. When the potential transpiration is hampered by the transient soil-water status, daily potential crop growth is reduced. The water-limited yield includes the effects of drought stress and waterlogging.

Long-term mean crop yields and coefficients of variance were obtained by running WOFOST for a period of 26 years using historical records of weather data. Simulated potential and water-limited yields refer to proper soil tillage, optimal application of nutrients, and optimal weed and disease control. WOFOST only simulates dry-matter increase and does not account for crop quality features, such as protein or moisture in wheat grain.

RESULTS

The potentially suited land for wheat-growing and the simulated wheat grain yields at different production levels are presented below. Results should be considered as a first quantitative approximation of the crop growth potential within the EC. The reliability of the results obtained can be improved when more basic soil, weather and crop cultivar data become available.

Suitability for wheat-growing

Screening the LEUs for crop and management requirements using qualitative land evaluation methods yielded an area potentially suited for mechanized wheat-growing of about 45% of the total EC. A major part of the EC is unsuited because of steep slopes (about 40% of EC has slopes of more than 15%), shallow soils and stoniness (25% of EC). Less important reasons for unsuitability are inadequate soil drainage and shallow rootable depth (8% and 5% respectively). Potentially suited land for mechanized wheat-growing throughout the countries of the EC is shown in Fig. 2. The percentage of suited land per country varies from 90% in Denmark to only 13% in Greece. A relatively low percentage of suited land, predominantly caused by steep slopes, occurs in the Mediterranean countries. In absolute size, large extents of suited land (> 50 000 km^2) occur in France, West Germany, the United Kingdom, and Spain.

Within the member states the percentage of suited land may vary remarkably between NUTS-1 regions (Table I). For example, in West Germany and France the percentages of land suited for mechanized wheat-growing vary between 30% and 90%. In the United Kingdom the suited area varies between 10% and 60%. Seven NUTS-1 regions, all located in the northern member

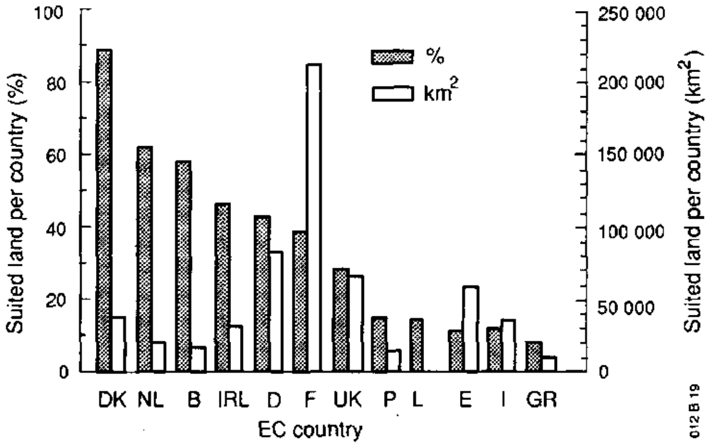

Fig. 2 Land suited for mechanized wheat-growing per EC member state (DK = Denmark, NL = Netherlands, B = Belgium, IRL = Ireland, D = West Germany, F = France, UK = United Kingdom, P = Portugal, L = Luxembourg, E = Spain, I = Italy, GR = Greece).

states, have a potentially suited area of more than 75%. On the other hand, 16 NUTS-1 regions located in the Mediterranean countries and the United Kingdom have a potentially suited area of less than 25%.

The estimated area unsuited for mechanized wheat-growing agrees reasonably well with earlier assessments. Lee (1987) estimated the area of moderately/poorly suited and unsuited land for arable farming at about 63% of the then ten member states, whereas Buringh et al. (1979) appraised the area of non-potential agricultural land at about 57% of the twelve member states. Our estimate of 55% unsuited land for wheat-growing is a lower limit for rainfed circumstances, because soils in dry regions with no other limitations than a low soil-water availability, were evaluated as potentially suited. Despite expected low water-limited yields these soils were not excluded by the mixed qualitative/quantitative land evaluation method, because otherwise the potential yield under irrigated conditions could not be quantified.

The relatively high percentages of unsuited land in some EC regions, especially in the Mediterranean countries, are confirmed by Buringh et al. (1979), Lee (1987), and De la Rosa et al. (1990).

Wheat grain yield

Long-term mean **potential wheat grain yield** simulated by WOFOST is presented for agro-climatic regions in Fig. 3. The yield data refer only to the potentially suited land within the agro-climatic region. Potential grain yield is particularly determined by the temperature regime and global radiation during the grain-filling period. The highest yields of over 10 t ha^{-1} grain dry matter are found in agro-climatic zones along the Atlantic Coast from Porto to Plymouth. Yields of slightly below 10 t ha^{-1} are found in more northerly Atlantic zones in the United Kingdom and Ireland. For most other regions the potential yield is between 7 and 9 t ha^{-1} grain dry matter.

Table I Percentage of suited land for mechanized wheat-growing for some selected NUTS-1 region within the EC.

NUTS-1 region	Suited land %	NUTS-1 region	Suited land %
West Germany		*Netherlands*	
Schleswig-Holstein	87	Oost-Nederland	93
Niedersachsen	74	Zuid-Nederland	97
Hessen	44		
Rheinland-Pfalz	28	*Belgium*	
Bayern	43	Vlaams Gewest	99
France		*United Kingdom*	
Bassin Parisien	72	East Midlands	48
Nord-Pas-de-Calais	83	Yorkshire & Humberside	23
Centre-Est	32	East Anglia	63
Mediterranee	29	South-East	55
Ouest	62	North-West	15
Sud-Ouest	60	North	9
		Scotland	19
Italy			
Nord-Ovest	20	*Denmark*	
Centro	23	Denmark	90
Lazio	13		
Campania	12	*Greece*	
Abruzzi-Molise	15	Ellas (North)	14
Sud	24	Ellas (Central)	11
Sardegna	10	Ellas (East, S. isl.)	10
Spain		*Portugal*	
Noroeste	18	Norte do Continente	25
Centro	44		
Sur	50		

Major exceptions are some cold regions, e.g. land above 300 m altitude in Scotland, and some very warm regions in Greece. In these regions potential yields are lower than 7 t ha^{-1} grain dry matter. Mean potential wheat yields aggregated at country level are presented in Table II. The country yields on potentially suited land vary between 6.7 t ha^{-1} in Greece and 9.4 t ha^{-1} grain dry matter in some countries along the Atlantic Coast.

The distribution of the long-term mean **water-limited wheat grain yield** for the potentially suited areas of the agro-climatic regions is shown in Fig. 4. Differences between potential and water-limited wheat yields are mainly related to drought stress during the grain-filling period. Drought stress depends on the earliness of the crop, the rainfall deficit, and the available soil water. The latter is related to soil texture, soil depth, groundwater influence, and runoff. In the temperate zone the summer rainfall deficit is rather low and the simulated yield reductions (relative to potential yield) are generally less than 10% on deep, medium-textured soils. On sandy and shallow soils, however, reductions by up to 50% occur. In the Mediterranean zone the

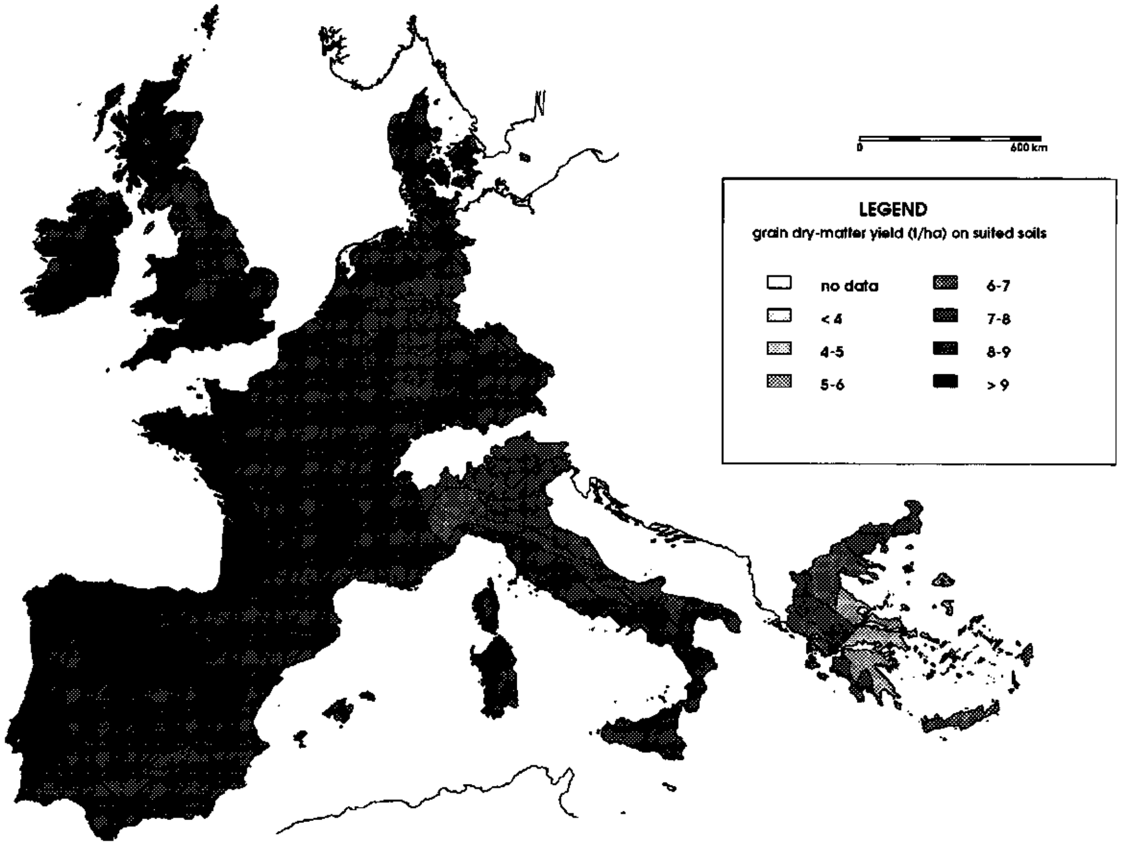

Fig. 3 Simulated mean potential wheat yield for agro-climatic regions in the EC; yields only apply to the potentially suited areas.

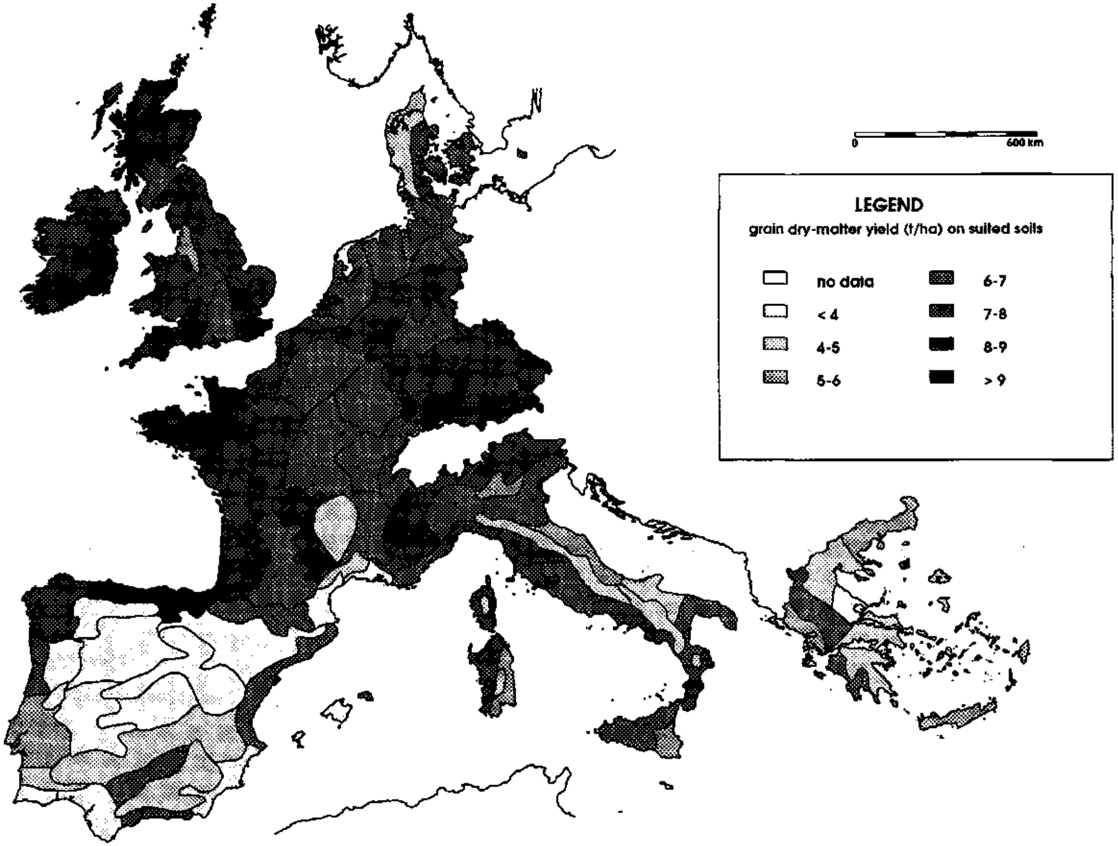

Fig. 4 Simulated mean water-limited wheat yield for agro-climatic regions in the EC; yields only apply to the potentially suited areas.

summer rainfall deficit is usually so large that soil-hydrological conditions are directly reflected in the simulated water-limited yield. For instance, in some Greek regions the yield reduction equals about 20% on deep, medium-textured, groundwater-affected soils, whereas on similar soils with free drainage the reduction amounts up to 50%. On shallow, coarse-textured soils with free drainage, very severe reductions by more than 80% occur in these regions. Low water-limited yields, less than 4 t ha^{-1}, were calculated for regions with a cold winter and a hot, dry summer, such as the Spanish high plateau. When the winter is milder, the crop develops earlier, benefits more from winter and spring rains, and reaches maturity before the severe summer drought. Mean water-limited wheat yields on potentially suited land aggregated at country level are presented in Table II. The figures clearly reflect the major climatic differences within the EC. Mean yields between 6 and 8 t ha^{-1} were calculated for suited land in the northern member states, whereas in most Mediterranean countries the yield is between 4 and 5 t ha^{-1} grain dry matter.

Table II Simulated long-term mean potential and water-limited wheat yields of areas suited for mechanized wheat-growing, mean actual wheat yield[1)] (in dry matter), and yield ratio (actual yield divided by water-limited yield) in the EC member states

Member state	Yield (t ha^{-1} yr^{-1})			Yield ratio
	potential	water-limited	actual	
West Germany	8.2	7.2	4.9	0.70
France	8.8	7.2	4.8	0.65
Italy	7.7	6.2	2.3	0.35
Netherlands	8.2	7.0	6.1	0.85
Belgium	8.2	7.1	5.2	0.75
Luxembourg	8.2	6.3	3.3	0.55
United Kingdom	9.2	7.5	5.6	0.75
Ireland	9.4[2)]	8.5[2)]	5.8	0.70
Denmark	8.2	5.8	5.5	0.95
Greece	6.7	5.3	2.1	0.40
Spain	8.7	3.8	2.2	0.60
Portugal	9.1	4.8	1.2	0.25

[1)] mean yield derived from 1983-1986 data (Eurostat, 1988) assuming a grain moisture content of 16%

[2)] yields can only be attained when specific measures are taken (see text)

The simulated high yields in moist regions, e.g. Ireland, can only be attained when diseases are prevented. High application rates of biocides will probably be needed. Moreover, the moisture content of the wheat grain will be high in these regions. Powerful drying facilities will be necessary.

Regional crop yields for several production situations were primarily simulated to investigate land use options within the EC. Land use is likely to change because of the existing cereal surpluses for food and fodder purposes. Wheat production volume should not expand anymore, although wheat yields (in t ha^{-1}) will continue to increase as long as farming practices are not adapted. First, the attainable wheat production will be presented in case the yield continues to increase while the current area is not reduced. Next, the results of some set-aside scenarios aimed at reducing cereal surpluses are given. In these scenarios emphasis is laid on effects of set-aside of either highly productive land or marginal land on regional production reduction.

Wheat production increase

Regional wheat production increase can be indicated by comparing the simulated grain yields of both water-limited and potential circumstances and the actual yield at NUTS-1 level. The increase from the actual situation to water-limited conditions can be attained without implementing major drainage and irrigation works. Actual and simulated NUTS-1 wheat grain yield data (Table II) can be aggregated to country or EC level by using the GIS. In Table II the ratio between actual wheat yield and water-limited yield is presented for each member state. High yield ratios, indicating limited possibilities for yield increase, occur in Denmark and the Netherlands, e.g. about 0.95 and 0.85. Yield ratios smaller than 0.40 occur in Greece, Italy and Portugal, expressing much potential for yield increase even under water-limited conditions. Yield ratios also differ between the NUTS-1 regions. These ratios and some statistical data for certain major wheat-producing regions in the EC are presented in Table III. In East Anglia and Bassin

Table III Current wheat area, wheat production, and ratio of mean actual and water-limited wheat grain yield in some selected NUTS-1 regions, ranked according to the relative importance of current wheat area.

NUTS-1 region	Current wheat area		Current wheat production1) (t)	Yield ratio
	% of NUTS-1 region	km²		
East Anglia (UK)	0.27	3 390	1 950 000	0.78
East Midlands (UK)	0.23	3 560	2 010 000	0.76
Bassin Parisien (F)	0.17	24 580	13 000 000	0.78
South-East (UK)	0.17	4 730	2 640 000	0.78
Sud (I)	0.16	5 190	980 000	0.22
Centro (I)	0.14	5 890	1 870 000	0.61
Abruzzi-Molise (I)	0.13	7 500	440 000	0.39
Ouest (F)	0.09	7 860	3 270 000	0.49
Bayern (D)	0.07	4 800	2 270 000	0.63
Sur (S)	0.06	6 090	1 590 000	0.57
Centro (S)	0.05	10 120	1 870 000	0.61
Sud-Ouest (F)	0.04	4 650	1 730 000	0.48
Centre-Est (F)	0.04	3 200	1 250 000	0.59

1) mean area and production derived from 1983-1986 data (Eurostat, 1988) assuming a grain moisture content of 16%

Parisien (Paris Basin), a yield increase by at least 20% might still be realized. In some regions the actual yield might even be doubled.

The attainable annual EC wheat production (in tonnes) on current wheat land can be calculated by multiplying attainable grain yield per hectare of land by the area of the NUTS-1 regions presently under wheat. As a land use map is lacking and hence the distribution of the current wheat land over the LEUs within a NUTS-1 region is unknown, the mean simulated yield for the potentially suited area of a NUTS-1 region was used. Attainable wheat production on the current wheat area, related to current EC wheat production volume, is presented for the EC member states and the whole EC in Table IV. Three production situations were distinguished, namely the simulated potential and water-limited productions and the actual production derived from statistics (Eurostat, 1988). On the current EC wheat area about 65% more wheat could be produced under water-limited and about 120% more under potential production conditions. Considerable potentials for production increase on the current area occur in France and Italy. France and Italy together could supply more than 90% of the current EC wheat production volume under water-limited conditions. Under potential conditions their wheat production even exceeds the current production volume.

Table IV Normalized wheat production on the current wheat area in the EC member states and the whole EC for different production situations (100 = 60 000 000 t grain dry matter [1]).

Country	Potential	Water-limited	Actual
West Germany	22	20	13
France	74	59	40
Italy	44	34	12
Netherlands	2	2	2
Belgium	3	2	2
Luxembourg	0	0	0
United Kingdom	27	22	17
Ireland	1	1	1
Denmark	4	3	3
Greece	10	8	3
Spain	30	13	8
Portugal	4	2	1
EC	220	165	100

[1] mean production derived from 1983-1986 data (Eurostat, 1988) assuming a grain moisture content of 16%

Set-aside of land

Setting aside land to reduce cereal surpluses is an area-oriented approach to solve a volume-oriented problem. Usually a linear relationship between reduction in area and production volume is supposed, irrespective of setting aside highly productive or marginal land. The influence of the yield potential of land on the impact of set-aside on regional production was explored by considering the range in simulated water-limited wheat grain yields within the area classified as potentially suited for wheat-growing. For each administrative region the cumulative areal distribution of the simulated water-limited LEU yields was calculated. Such distributions for two major wheat-growing regions, namely Bassin Parisien and East Anglia (Table III), are presented in Fig. 5.

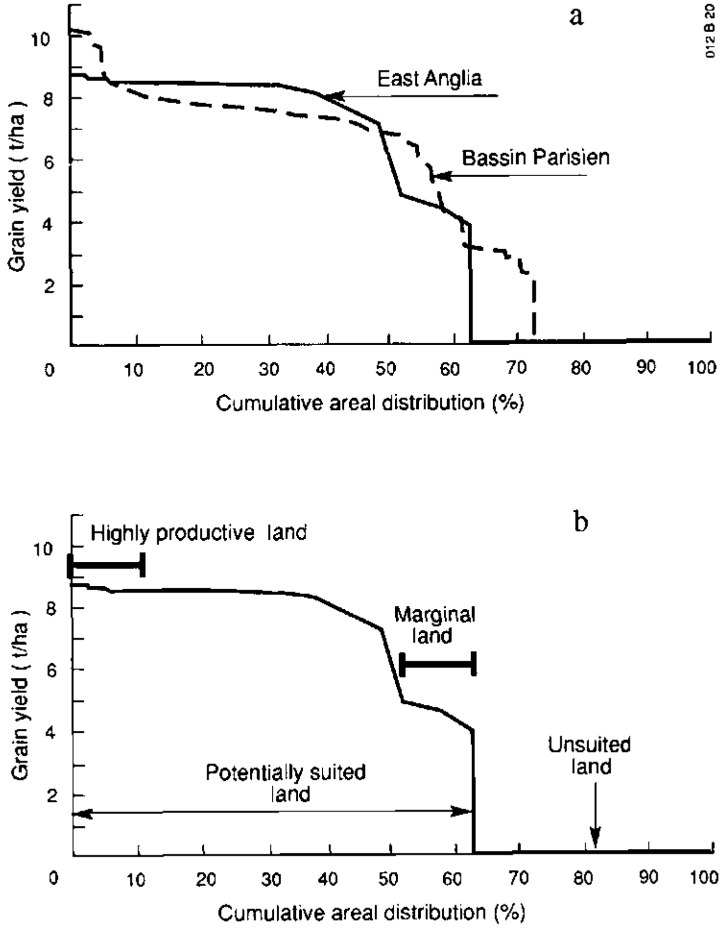

Fig. 5 Cumulative areal distribution of water-limited yields for the NUTS-1 regions of East Anglia and Bassin Parisien (a) and indication of the highly productive and marginal land of the potentially suited area in East Anglia (b)

About 65% of the NUTS-1 region of East Anglia was considered to be suited for wheat-growing and the water-limited yields varied from 4 t ha^{-1} to slightly above 8.5 t ha^{-1} grain (Fig. 5b). If 10% of the most productive land of East Anglia land would be set aside and used for other purposes, the reduction in production volume would be about 8.7 t ha^{-1} land set aside (Fig. 5b). However, when 10% marginal land, which still belongs to the potentially suited area, would be set aside, the mean production decline would be significantly smaller, e.g. about 4.2 t ha^{-1} land set aside. So, in the case of East Anglia if the marginal land is set aside, the reduction in wheat production volume will be about 50% of the reduction reached by setting aside highly productive land. In the Bassin Parisien the yield difference between highly productive and marginal land is even more pronounced than in East Anglia (Fig. 5a). If the marginal land of the Basin Parisien would be set aside, production volume decrease will be only about 35% of the reduction achieved with highly productive land.

The cumulative areal distributions of the simulated water-limited wheat grain yields of the NUTS-1 regions were used to examine the effect of setting aside either marginal land or highly productive land in the EC as a whole. Depending on the extent of the area to be set aside, marginal land produces 40% to 55% less wheat than highly productive land. In other words, achieving a specific reduction in wheat production volume will require the set-aside of twice as much marginal land as highly productive land.

CONCLUSIONS

Physical land evaluation methods, combining expert knowledge and simulation modelling, which are linked to a GIS, were shown to be effective to investigate EC crop growth potential on different spatial aggregation levels. Use of expert knowledge, captured in a computer system, to screen land for potential suitability, and subsequent application of simulation modelling to potentially suited land only, appears to be very functional. The linkage of physical land evaluation models and a GIS substantially improves usefulness of these tools. Evaluation models have better access to basic data and enable the GIS to analyse and present interpreted data, which are usually more relevant to policy-making than the basic data itself.

Current land use problems within the EC can only be effectively settled if several land use options are comprehensively evaluated. Sophisticated land use planning tools are proposed to explore these options, demanding quantitative input data. The combined approach, explained in this contribution, is expected to be a useful part of these tools because it renders the required quantitative data on agro-ecological potential.

Although the reliability of the predicted regional crop growth potential can be improved, predominantly by collecting more basic data, some relevant conclusions on the growth potential and its effects on some land use options may already be drawn.

A considerable area of the EC is unsuited for mechanized agriculture. Unsuited land is unequally distributed over the EC. Important for rural development possibilities are the relatively high percentages of unsuited land which occur in some EC regions, especially in the Mediterranean countries. Although more than half of the EC is unsuited for mechanized agriculture, the crop production potential of the remaining, suited land is still high. For instance, on the current wheat area the EC production volume might grow by 65% and 120% under water-limited and potential conditions respectively. For large areas of agricultural land alternatives for surplus crops, such as wheat, have to be found.

In many EC regions the impact of set-aside of land on reduction of the wheat production volume strongly depends on the production potential of land. As a whole, the water-limited wheat yields of marginal land in the EC are 40% to 55% less than those of highly productive land. In some major wheat-producing regions in France and the United Kingdom, highly productive land produces two or three times as much wheat as marginal land. Hence, measures aiming at production reduction should not only refer to the area to be set aside, but also take into account the production potential of the land.

ACKNOWLEDGEMENTS

The initiation of this study by Prof. R. Rabbinge (Dutch Scientific Council for Government Policy (WRR) and Agricultural University, Wageningen) and his stimulating support are gratefully acknowledged. The WRR funded this study and gave permission for early publication of the results. A digitized EC soil map and a map with administrative regions were kindly supplied by the CORINE project team (CEC). In this context the support of Ir. J. Maes (CORINE) was invaluable. Dr. D. Rossiter (Cornell University, New York State) provided major support by adapting ALES. We also acknowledge Prof. J. Bouma (Agricultural University, Wageningen) for critically reading the text and suggesting improvements.

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8 USE OF SIMULATION TO ASSESS THE EFFECTS OF DIFFERENT TILLAGE PRACTICES ON LAND QUALITIES OF A SANDY LOAM SOIL

Published in Soil & Tillage Research 10(1987), 4: 347-361

Use of Simulation to Assess the Effects of Different Tillage Practices on Land Qualities of a Sandy Loam Soil

H.A.J. VAN LANEN, M.H. BANNINK and J. BOUMA

Netherlands Soil Survey Institute, P.O. Box 98, 6700 AB Wageningen (The Netherlands)

(Accepted for publication 5 June 1987)

ABSTRACT

Van Lanen, H.A.J., Bannink, M.H. and Bouma, J., 1987. Use of simulation to assess the effects of different tillage practices on land qualities of a sandy loam soil. *Soil Tillage Res.*, 10: 347-361.

Four different soil-structure types could reproducibly be recognized by soil surveyors working on Dutch sandy loam soils with different management practices. The 4 structure types were soils with a primary ploughpan, a loosened ploughpan, a secondary ploughpan and a grassland structure. These types had significantly different soil-physical properties and rooting depths. Soil-water regimes for a 30-year period were simulated to obtain quantitative information on the influence of soil structure, as an expression of different soil-management practices, on land qualities such as moisture deficit, aeration status and workability.

These land qualities were not significantly different for the 3 structure types of arable land when considering the entire soil profile. However, differences in moisture content and aeration status were significant when undisturbed and disturbed ploughpans were compared. Deep ploughing to disrupt the primary ploughpan should therefore not be encouraged in these soils as long as common field operations remain unchanged. The same land qualities for grassland indicated what may be attained by soil-structure regeneration. The probability of having a workable day in spring or autumn is increased by an estimated 20%, and the number of days with adequate aeration by 10%, in soil-structure types of arable land (A, B and C) as compared with grassland soil structure (D). Moisture deficits in the growing season should be about 50% less.

In this study, simulation was not used to simulate soil-structure formation as a function of soil management, but soil structure was used as an input for the models, reflecting different management practices. To that end, the various structure types were characterized by physical measurements.

INTRODUCTION

The feasibility of using computer-simulation models for defining soil-water regimes and associated land qualities, such as moisture deficit, aeration status and workability, has been demonstrated in several studies (e.g. Belmans et al., 1984; Buitendijk, 1985; Wösten and Bouma, 1985; van Wijk and Feddes, 1986).

Soil-physical properties, rooting data, weather conditions and water-tables are needed as input data. Soil-tillage operations change physical properties, such as moisture retention and hydraulic conductivity (Canarache et al., 1984; Kooistra et al., 1984, 1985), and rooting patterns (Boone et al., 1978, 1985; Ehlers et al., 1980). Simulation models are therefore becoming attractive tools for predicting the effects of different soil-management practices on important land qualities for land evaluation. A land quality is a complex attribute of land, which acts in a distinct manner in its influence on the suitability of land for a specific kind of use. Examples are moisture deficit, aeration status and workability (FAO, 1976).

In The Netherlands, ploughpans are common in medium-textured cultivated soils. Attempts have been made to remove the ploughpans. In sandy loam soils, these cultivation actions have resulted in 4 different soil-structure types, which could reproducibly be distinguished in the field by soil surveyors, as has been described elsewhere (Kooistra et al., 1985). The types have the following specific features: (A) a primary ploughpan; (B) a loosened, uncompacted ploughpan; (C) a secondary ploughpan, formed after loosening the primary ploughpan and renewed compaction; (D) no ploughpan in soils used as permanent grassland.

The hydraulic conductivities (k-h) and the moisture retentions (h-θ) of the layers just below the ploughlayers, and the rooting depths were significantly different. These results only have significance for land-evaluation purposes if they are used in a comprehensive model simulating soil-water dynamics over a number of years, so allowing the quantification of important practical land qualities, such as moisture deficit, aeration status and workability (FAO, 1976; Bouma, 1984). Therefore, the object of this study was to quantify the above-mentioned land qualities for the 4 soil-structure types distinguished in sandy loam soils, thereby expressing effects of different soil-management practices. Seasonal and annual variation in weather conditions were considered by making calculations for a 30-year period. Thus, probability estimates could be provided.

MATERIALS AND METHODS

Soil-structure types and physical properties

The sandy loam soils studied are located in the south-west of The Netherlands near Nieuw-Vossemeer. They have been developed in calcareous, medium-textured, young marine deposits and are classified as Typic Fluvaquents (Kooistra et al., 1985). The soils are mainly in use as arable land, and have a crop rotation of potatoes, sugar beets and winter wheat. In arable land, 3 clearly different soil-structure types can be distinguished by detailed field observations, such as soil-structure description in profile pits and penetrometer mea-

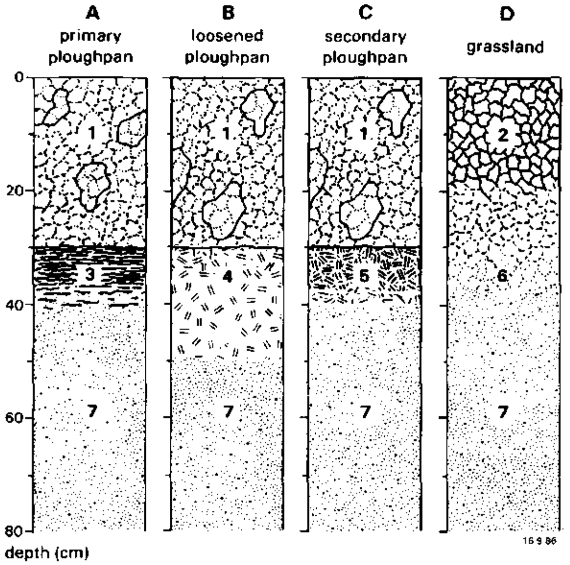

Fig. 1. Soil structures in a sandy loam soil; figures indicate layers with different soil structures and physical properties.

surements (Kooistra et al., 1985). These structure types have been defined in terms of properties of the soil layer at a depth of 30–45 cm. The layers have significantly different soil-physical properties (k-h and h-θ), whereas the other soil horizons (ploughlayer 0–30 cm and subsoil deeper than 45 cm) do not differ significantly. In addition to the 3 soil-structure types related to arable land, a fourth type found in grassland can be distinguished. Soil structures and physical properties of the surface horizons to a depth of 45 cm in grassland differ clearly from the structure types in arable land. However, the physical properties of the subsoils below 45-cm depth are comparable. Summarizing, four different soil-structure types could be distinguished, as is illustrated in Fig. 1. Some relevant soil data on the different soil-structure types are listed in Table I. The soil-physical data (k-h and h-θ) used were measured by Kooistra et al. (1985).

Data for the simulation model

The simulation model used (ONZAT) was proposed and validated by van Drecht (1985). It has been derived from the model SWATRE, which has been extensively validated for various crops and soil types (e.g. Belmans et al., 1984; Feddes and De Graaf, 1985; van Wijk and Feddes, 1986). ONZAT simulates transient, one-dimensional soil-moisture flow in a vertical soil column. The partial, non-linear differential equation, describing unsaturated moisture flow,

TABLE I

Analytical and soil-physical data for the different layers (see Fig. 1) of the sandy loam soil

Layer	f_{Lm}	f_{h}	ρ_{d} (g cm^{-3})	h (cm)									
				0		−10		−100		−1000		−10 000	
				θ	k (cm day^{-1})	θ	k (cm day^{-1})	θ	k (cm day^{-1})	θ	k (cm day^{-1})	θ	k (cm day^{-1})
1	0.14	0.018	—	0.38	48	0.36	2.0	0.28	0.095	0.21	4.0×10^{-3}	0.16	3.0×10^{-4}
2	0.12	0.043	1.35	0.49	2500	0.47	8.3	0.40	0.75	0.24	4.0×10^{-3}	0.14	1.5×10^{-4}
3	0.10	0.008	1.62	0.37	8.5	0.36	1.4	0.29	0.026	0.19	2.1×10^{-3}	0.12	1.4×10^{-4}
4	0.09	0.006	1.33	0.42	300	0.41	4.4	0.27	0.015	0.11	1.8×10^{-5}	0.05	4.0×10^{-8}
5	0.09	0.006	1.58	0.37	3	0.36	0.6	0.30	0.032	0.19	6.0×10^{-4}	0.12	3.8×10^{-5}
6	0.11	0.028	1.43	0.43	180	0.39	15	0.31	0.03	0.18	8.5×10^{-4}	0.09	4.0×10^{-5}
7	0.05	0.004	1.55	0.41	45	0.39	18	0.34	0.7	0.05	1.4×10^{-3}	0.03	5.5×10^{-5}

f_{Lm} = Clay content (g g^{-1}); f_{h} = organic-matter content (g g^{-1}); ρ_{d} = bulk density (g cm^{-3}); θ = moisture retention (cm^3 cm^{-3}); k = hydraulic conductivity (cm day^{-1}); h = pressure head (cm).

is numerically solved using an implicit finite-difference technique. The soil column is therefore divided into layers with nodal points in the middle (nodal distance 5–15 cm) and time is divided into steps (0.001–1 day). The driving variables are daily rainfall and potential evapotranspiration at the upper boundary, and water fluxes at the lower boundary. Water uptake by plant roots occurs from a variable number of soil layers, corresponding with increasing rooting depths during the growing season. Each soil layer of the soil column has to be characterized by soil-physical data ($k-h$ and $\theta-\mathrm{h}$), allowing the definition of a layered soil profile. ONZAT can also be used for simulating real evapotranspiration of agricultural crops. Moreover, the model calculates pressure heads, moisture contents, and air-filled porosities as functions of depth and time.

Calculations were made for the period 1955–1984, for a potato crop. Potatoes are sensitive to soil compaction so, if there are differences in land qualities due to compaction, potatoes are bound to show them sooner than, for instance, winter wheat or sugar beet. The choice of a 30-year period was based on the assumption that meteorological conditions recorded in the past will also be representative for the future. Thus, probability estimates can be provided for the various land qualities. Precipitation and open-water evaporation (E_o) were derived from 10-day sums of the Oudenbosch, a nearby meteorological station. Potential evapotranspiration (E_{pot}) was estimated using crop coefficients (f) and E_o as follows: $E_{pot}=fE_o$ (see also Doorenbos and Kassam, 1979). For fallow soil $f=0.3$ is used (10 September–10 May). During the growing season, related to the stage of development of the potatoes, the crop coefficient increases from $f=0.3$ (10 May) to $f=0.9$ (20 June). Then the crop coefficient remains constant at $f=0.9$ until 10 August, and from then it decreases to $f=0.6$ until the potatoes are lifted (10 September).

Rooting depths differ for the 4 soil structures, and depend also on the stage of development of the crop. The rooting depths of soil profiles with primary and secondary ploughpans are shallow in the initial crop-growth stage (5 cm). Later, depths linearly increase to 30 cm (June–mid-July), and then they remain at a depth of 30 cm until harvesting time (September). The loosened ploughpan and the profile with the soil-structure of grassland have higher maximum rooting depths, viz. 65 cm. In these soils the rooting depths increase linearly from 5 to 65 cm (June and July), and then remain at 65 cm. These figures are based on rooting-pattern analyses in profile pits as described by Kooistra et al. (1985), and on data from Boone et al. (1978, 1985). Crop coefficients for estimating E_{pot} and rooting depths depend on the stage of development of the crop, but are assumed to be identical for each year irrespective of climatic and soil conditions.

Water extraction by roots is simulated in accordance with a simple sink term proposed by Hoogland (1980). The water-extraction pattern is from top to bottom, as long as the pressure head of the nodal points belonging to the rootzone is not below a critical value. According to M. de Graaf (personal communication 1985), this critical value for the potato crop depends on the magnitude of the potential evapotranspiration, and drops from $h = -350$ cm ($E_{pot} = 0.5$ cm day^{-1}) to $h = -600$ cm ($E_{pot} = 0.1$ cm day^{-1}). If the pressure head of one or more of the nodal points in the rootzone falls below this critical value, water will preferentially be extracted from the wetter layers within the rootzone. When the water demand (E_{pot}) of the crop cannot be met by any of these layers without exceeding the critical value of the pressure head, water uptake will be less than the potential evapotranspiration and a moisture deficit will occur.

As no water-table data were available for a 30-year period, a relationship between flux and water table was adapted by iterating until the calculated mean highest and mean lowest water tables were equal to values estimated in the field by the soil surveyor (90 and 170 cm below the surface, respectively). Afterwards, the frequency distribution of the water tables calculated by the model is checked, because it has to correspond with the distribution derived from the observed mean highest and mean lowest water tables (van der Sluijs and de Gruijter, 1985).

Land qualities

The land quality "moisture deficit" is defined as the difference between the potential and actual evapotranspirations during a certain period of time. The simulation model ONZAT calculated the actual evapotranspiration and the moisture deficit, if any, on a daily basis.

The land quality "workability" was determined in accordance with the procedure proposed by van Wijk and Feddes (1986) and schematically summarized by Bouma and van Lanen (1987). The suitability of a soil for planting and harvesting operations depends on soil characteristics (e.g. texture, organic-matter and $CaCO_3$ content) and the moisture content or pressure head of the topsoil. If the pressure head is below a critical threshold value soil conditions allow field operations. Each soil has its own threshold value for workability. The threshold values of sandy loam soils usually range from $h = -80$ to $h = -100$ cm, reflecting the range from moderate to good soil conditions for field operations in spring (van Wijk and Feddes, 1986). Field observations in this study, and initial simulation output, resulted in a threshold value of $h = -70$ cm for the sandy loam soils considered here. No distinction had to be made between the 4 soil-structure types. Knowing the threshold value, we could derive the occurrence of workable days during the period 1955–1984 from simulated pressure heads at 5-cm depth, which differed for the 4 soil structures.

The air-filled porosity at a depth of 5 cm below soil surface was used as an indicator for the land quality "soil aeration". Air-filled porosity determines the diffusion coefficient of oxygen and carbon dioxide, and consequently the

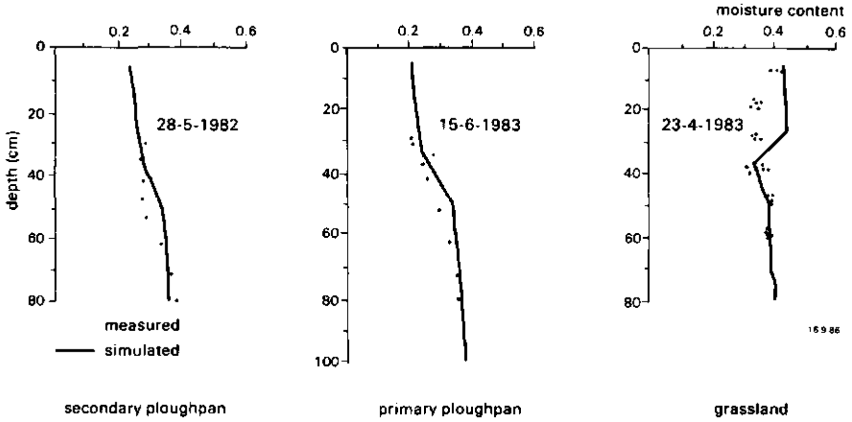

Fig. 2. Validation of the simulation model comparing measured and simulated soil-moisture contents.

diffusion rates of these gases in the soil. Soil aeration was assumed to be satisfactory when air-filled porosity was above a critical threshold value. This value differs for various crops, stages of development, and soil types. As a first approximation, a threshold value of 0.1 $m^3 m^{-3}$ has been proposed (e.g. Greenwood, 1975; Jayawardane and Meyer, 1984). Below this limit, aeration conditions are assumed to be inadequate for root growth. As in workability, the occurrence of days with adequate soil aeration can be derived from simulated air-filled porosities.

RESULTS

Validation of the model

Some selected field measurements and simulated moisture contents with depth are presented in Fig. 2. No data were available for a soil profile with a loosened ploughpan. Calculations for the soil profile with the structure of grassland were made with grass as a crop. With the exception of grassland at 20-cm depth, measured and simulated moisture contents corresponded well.

Moisture deficit

Results of the simulation are shown in 3 ways: (1) as a graph showing the cumulative moisture deficit during the dry year 1976 (Fig. 3); (2) as a graph showing the cumulative frequency distribution of the annual moisture deficit (Fig. 4); (3) as a graph indicating the probability of occurrence of a moisture deficit for each 10-day period during the growing season of potatoes (Fig. 5).

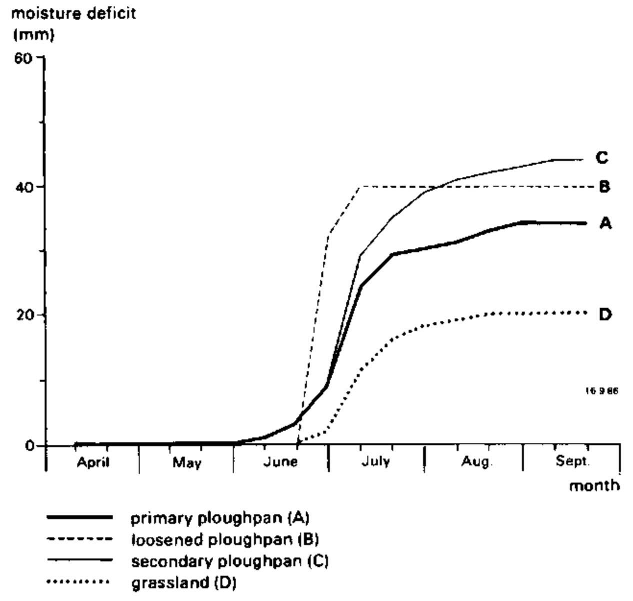

Fig. 3. Cumulative moisture deficits in 1976 of potatoes grown on sandy loam soils with different soil structures.

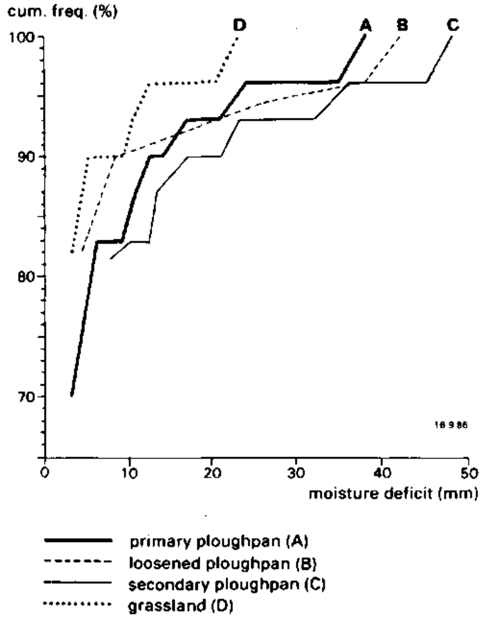

Fig. 4. Cumulative frequency distributions of annual moisture deficits of potatoes grown on sandy loam soils with different soil structures.

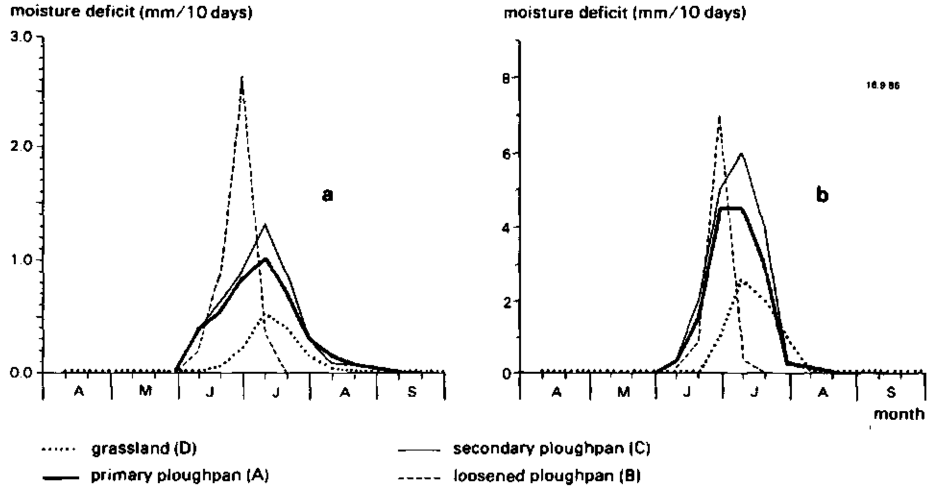

Fig. 5. Moisture deficits during the growing season of potatoes on sandy loam soils with different soil structures. a, Mean; b, 1 year out of 10.

Moisture deficits during the extremely dry year 1976 (probability of occurrence about 1%) were different for the four soil-structure types (Fig. 3). At the end of the growing season, potatoes grown on soil-structure Types A, B, C and D (Fig. 1) had moisture deficits of about 35, 45, 40 and 20 mm respectively. Figure 4 shows that a sandy loam under Dutch climatological conditions is unlikely to have moisture deficits, despite the occurrence of different soil structures. In 70–80% of the years no deficits will occur, and the maximum deficit will not be higher than 25–50 mm. However, small differences between the structure types occur. Figure 5 indicates that July has the highest probability for the occurrence of a moisture deficit in the Types A, C and D. For Type B this is 1 month earlier. Note, however, that the maximum mean moisture deficits (Fig. 5a) and the deficits for 10-day periods in 1 year out of 10 (Fig. 5b) are small for a sandy loam under Dutch climatological conditions, namely 3 and 7 mm per 10 days, respectively.

Owing to differences in tillage activities and consequently in soil-physical properties and rooting patterns, the ranking of the soil structures with respect to sensitivity for water shortage for potatoes, from high to low, is: (1) secondary ploughpan; (2) primary ploughpan; (3) grassland. Sometimes, potatoes on a loosened ploughpan suffer from water shortage (Fig. 5). These conditions prevail when the months of May and June are extremely dry, while the roots have not yet reached the unloosened subsoil. In 1976 these conditions occurred (Boone et al., 1978). The loosened ploughpan has such an unfavourable hydraulic conductivity that it prevents capillary rise from the groundwater when the water table is deeper than about 80 cm. After the roots have reached the undisturbed subsoil, they can benefit from the excellent hydraulic properties of this layer, and drought sensitivity is very small thereafter. With respect to drought sensitivity, the loosened ploughpan behaves, in most years, similarly to grassland, and in some dry years (one in ten) is comparable with the secondary ploughpan (Fig. 4).

Workability

The occurrence of workable days is presented as a probability graph in Fig. 6 (see also Wösten and Bouma, 1985). This graph indicates the probability of occurrence of a workable day for any day of the year, and was derived from simulated 24-hour data over a period covering 30 years. For a sandy loam soil, with a primary ploughpan, the probability of being able to work on the land on 1 May is about 70%, with 50% and 85% as upper and lower 95% confidence limits.

Important periods for the workability of soils when growing potatoes are the months of March and April, when field operations are needed for planting tubers, and September and October, when harvesting operations have to be performed. The probability of being able to work on a soil with a primary ploughpan in April ranges from 60% to 70%, with lower and upper 95% confidence limits of about 40% and 80%, respectively. These figures are in accordance with field observations of numbers of workable days, during a 20-year period on a similar soil, by Hokke (see Wind, 1976). In March, a decrease of workable days occurs owing to the generally higher total precipitation as compared with February and April. For the soil profiles with primary ploughpans the number of workable days in September is about equal to the number in April.

In Fig. 6, only estimates for the workability for soil profiles with primary ploughpans are presented, and not those of the secondary and loosened ploughpans, because they hardly differ. Soil profiles with a grassland soil structure, on the contrary, show higher probability estimates for workable days. In April and September the probability of having a workable day is 20–30% higher, and in March differences are even bigger (40–50%).

Smoothed 24-hour precipitation data (derived from 10-day sums) were used as upper boundary conditions for the simulation. The number of workable days increased by approximately 10% when a more irregular and realistic precipitation pattern was used. Small differences among arable soils did, however, not increase.

From soil-physical data presented by Kooistra et al. (1984, 1985) one representative moisture-retention and one hydraulic-conductivity curve was chosen for each soil layer, although a number of curves were available. Using the entire range of presented curves for the compacted ploughpans, the numbers of workable days or days with adequate aeration did not change by more than 10–15%.

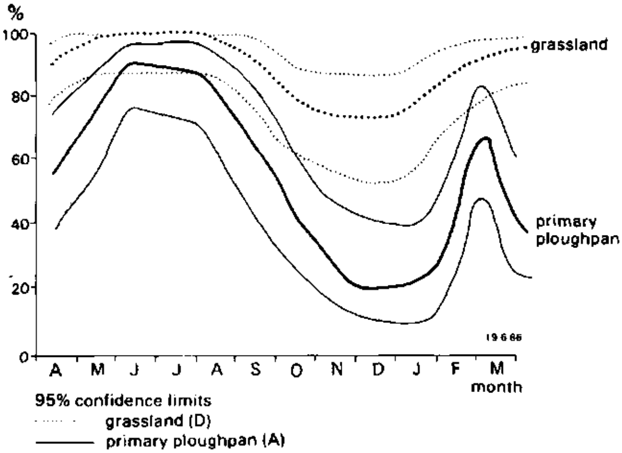

Fig. 6. Probabilities of occurrence of workable days on sandy loam soils with different soil structures.

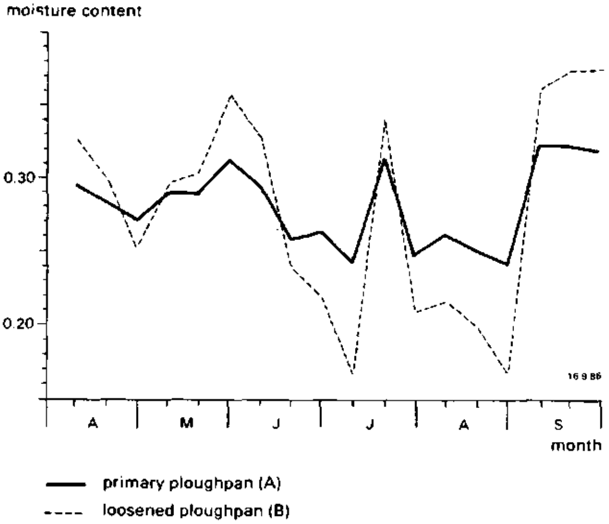

Fig. 7. Moisture contents in 1984 just below the tilled layer (35-cm depth) in sandy loam soils with loosened and undisturbed ploughpans.

As mentioned above, workability was derived from pressure heads at 5 cm below surface, which did not differ significantly between Types A, B and C. However, below the tilled layer differences do occur. Moisture contents of the loosened ploughpan are generally higher than those of the primary, compacted ploughpans (Fig. 7). Therefore, the layer just below the ploughlayer has a higher compaction risk in soil profiles with loosened ploughpans.

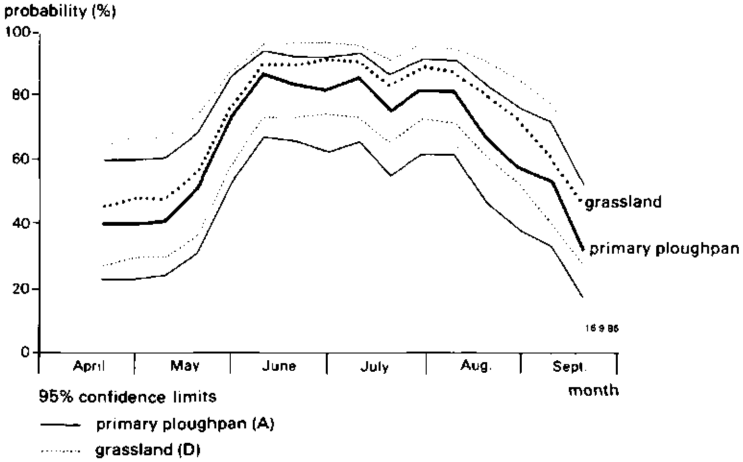

Fig. 8. Probabilities of occurrence of days with adequate aeration on sandy loam soils with different soil structures.

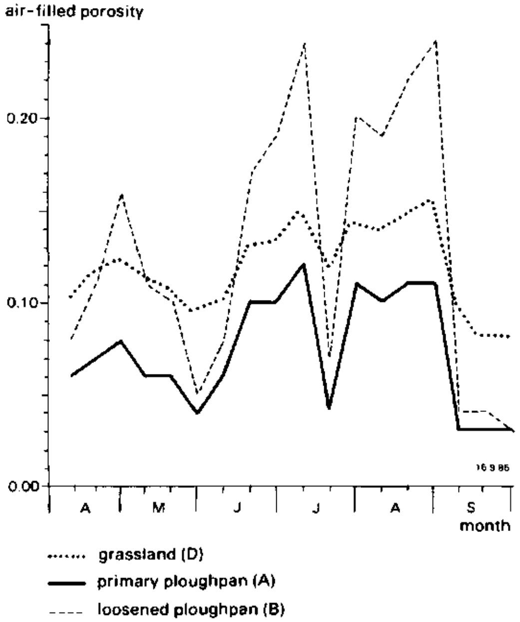

Fig. 9. Air-filled porosities in 1984 just below the tilled layer (35-cm depth) in sandy loam soils with loosened and undisturbed ploughpans, and grassland soil structure.

Soil aeration

The occurrence of a day with adequate aeration of the topsoil (air-filled porosity more than 0.1 $m^3\ m^{-3}$) is presented as a probability graph in Fig. 8.

For example, on 1 June the probability of occurrence of adequate aeration is 75%, with 50 and 90% as lower and upper 95% confidence limits for sandy loam soils in use as arable land. As in workability, differences between Types A, B and C are not significant. The aeration status of soil profiles with soil-structure Type D is significantly better than that of Types A, B and C. The probability of having adequate aeration in critical periods of the year is about 10% higher.

In contrast to the topsoil, aeration just below the tilled layer shows clear differences between the various soil-structure types. The compacted ploughpans have a significantly lower air-filled porosity than the loosened ploughpan. For instance, in the relatively wet year 1984, the air-filled porosity in soil-structure Type A hardly exceeded the critical value of 0.1 m^3 m^{-3}, whereas in Types B and D air-filled porosities were generally above this limit (Fig. 9). A nearly-constant air-filled porosity and therefore moisture content, such as shown for Type D, constitutes a very favourable condition for growing high-quality potatoes. Limited soil aeration and higher mechanical resistance (Kooistra et al., 1984, 1985) are the main reasons for shallow rooting depths as observed in sandy loam soils with compacted ploughpans.

CONCLUSIONS AND DISCUSSION

Under Dutch climatological conditions, loosening a ploughpan in a sandy loam soil did not result in increased numbers of workable days and days with adequate aeration. Owing to deeper root penetration, soil profiles with a loosened ploughpan (a situation which will only exist for a few years) usually have smaller moisture deficits than soils with compacted ploughpans. However, in 1 year out of 10 moisture deficits of potatoes grown on a loosened ploughpan are about equal to those of the compacted ploughpans. This may occur in a dry summer, when the roots have not yet reached the undisturbed subsoil. The secondary ploughpan, formed after renewed compaction, results in a lower moisture-supply capacity, and slightly smaller numbers of workable days and days with adequate aeration, than the primary ploughpan. Therefore, under Dutch climatological conditions, loosening the ploughpan of a sandy loam soil should not be encouraged. This is confirmed by the results of crop responses on sandy loam soils with different soil structures (Alblas, 1985).

More favourable soil-physical properties were observed in sandy loam soils under permanent grassland, with a relatively high biological activity resulting in a relatively porous soil structure. The results of an exploratory run using these data showed that grassland had a higher moisture-supply capacity, and higher numbers of workable days and days with adequate aeration, than arable land. These differences in land qualities can be interpreted to represent the maximum advantage to be attained by farmers when regenerating soil structure by, for example, minimum tillage, and by increasing organic-matter contents. Under Dutch circumstances, maximum benefits for these activities amount to a decrease of about 10% in the number of years in which a deficit occurs. In dry years, the deficits are reduced by 50%. Structure improvement may result in maximum increases of workable days and days with adequate aeration by about 20 and 10%, respectively.

These results illustrate the use of simulation to characterize physical soil conditions in quantitative terms, as functions of different soil-management practices. Actual but also potential conditions can be simulated, to provide information about the feasibility of innovative soil-management practices or rational planning of new short-term field experiments. This project demonstrates the use of simulation models for water regimes, incorporating measured physical properties and rooting depths, for different observed soil-structure types. These types, in turn, are representative of different soil-management practices, as appeared from interviews with farmers and county agents. This approach may be more attractive, for practical applications, than trying to predict the effects of compaction itself by simulation, which is very difficult for field conditions. This project also demonstrates the use of simulation for predicting long-term data, which would be impossible to obtain by monitoring owing to obvious budgetary and practical limitations.

ACKNOWLEDGEMENTS

The authors are indebted to O.H. Boersma, who measured soil-moisture contents, rooting depths and physical data. Ir. J.H.M. Woster assisted with running the simulation model.

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9 THE EFFECT OF BYPASS FLOW AND INTERNAL CATCHMENT OF RAIN ON THE WATER REGIME IN A CLAY LOAM GRASSLAND SOIL

Published in Journal of Hydrology 95(1987), 1/2: 1-11

THE EFFECT OF BYPASS FLOW AND INTERNAL CATCHMENT OF RAIN ON THE WATER REGIME IN A CLAY LOAM GRASSLAND SOIL

T.P.J. VAN STIPHOUT[1], H.A.J. VAN LANEN[2], O.H. BOERSMA[3] and J. BOUMA[4]

[1]*University of Amsterdam, Dapperstr. 115, 1093 BS Amsterdam (The Netherlands)*
[2]*Land Use Department, Netherlands Soil Survey Institute, P.O. Box 98, 6700 AB Wageningen (The Netherlands)*
[3]*Soil Structure and Micromorphology Department, Netherlands Soil Survey Institute, P.O. Box 98, 6700 AB Wageningen (The Netherlands)*
[4]*Agricultural University, P.O. Box 37, 6700 AA, Wageningen (The Netherlands)*

(Received December 27, 1986; revised and accepted May 19, 1987)

ABSTRACT

Van Stiphout, T.P.J., Van Lanen, H.A.J., Boersma, O.H. and Bouma, J., 1987. The effect of bypass flow and internal catchment of rain on the water regime in a clay loam grassland soil. J. Hydrol., 95: 1–11.

Bypass flow was studied in a clay loam grassland soil with a loamy subsoil by means of laboratory experiments on large, undisturbed columns of surface soil. At a pressure head (h) of -1000 cm, bypass flow averaged 45% and at $h = -200$ cm 70% of applied rain (intensities of 20 and 35 mm h^{-1}). Depth of infiltration of bypass water was studied in the field using morphological staining techniques and an infiltration experiment. Water, flowing into continuous cracks and worm channels, infiltrated into the subsoil at 60 and 135 cm depth respectively. This subsoil infiltration was called "internal catchment". Thus, the infiltration process differs from the classical concept of surface infiltration. Simulation with 1986 weather data was used to explore the effects on the water regime. Results indicate that crop water deficits differ significantly when bypass flow and internal catchment are taken into account.

INTRODUCTION

Field and laboratory investigations have shown that bypass flow is common in cracked heavy clay soils in the Netherlands (Bouma et al., 1978, 1981; Hoogmoed and Bouma, 1980) and elsewhere (e.g. Boumans, 1982; Beven and Germann, 1982; White, 1985). Bypass flow describes the vertical movement of free water along macropores (cracks and worm channels) through an unsaturated soil matrix. The heavy clay soils studied had continuous cracks reaching into the subsoil, which resulted in loss of water to the grass crop. However, little is known about the extent of bypass flow in other soils with vertically discontinuous macropores and with lower clay contents. Accordingly, this study was planned to investigate bypass flow phenomena in soils consisting of a cracking clay loam sediment of approximately 60 cm thickness covering a noncracking loamy subsoil. In these soils, vertical cracks extend only to the loamy subsoil. Water which flows along their walls constitutes bypass flow, and will have to infiltrate directly into the loamy subsoil. This type of subsoil infiltration, also mentioned by Beven and Germann (1982), has so far not been defined and will henceforth be called "internal catchment". It constitutes a specific characteristic of the widely occurring well-drained sedimentary clay loam soils where clay content decreases with depth.

In old grassland soils, the situation is further complicated by the occurrence of many worm channels that often go deeper than the cracks and extend into the loamy subsoil. Bypass flow, infiltrating through these channels, will infiltrate at the depth where the channels end (Edwards et al., 1979). Field observations suggest that internal catchment is a possible reason for irregular water contents with depth (e.g. Becher and Vogl, 1984). The phenomenon is likely to have consequences when calculating water balances and water uptake by crops. In particular, crops with a shallow rooting system like grassland, are assumed to suffer earlier from water stress when bypass flow and internal catchment occur.

Simulation of soil water flow and evapotranspiration was used in this study to explore the consequences of the described processes for the soil water regime in a clay loam soil.

To summarize, the objectives of this study were to: (1) quantify bypass flow; (2) determine depths to which it penetrates; and (3) estimate the effects of bypass flow and internal catchment on soil moisture availability for permanent grassland.

SOILS AND METHODS

Soils

The soil studied is a fine-silty, mixed (calcareous), mesic Typic Fluvaquent (De Bakker, 1979), located at Piershil, 15 km south of Rotterdam. The soil has a clay loam topsoil (31% clay and 36% silt) with a strong fine prismatic structure, and a colour of 10YR 4/1 (moist). It is rich in organic matter (5.6%) and lime (6.0%). In the subsoil the clay content decreases to a loam texture (18% clay) at 120 cm depth. The mean highest water table is at a depth of 70 cm and the mean lowest water table at a depth of 180 cm below the surface (Van der Sluijs and De Gruijter, 1985). Land use has been extensive permanent grassland for decades.

Experiments in the field

Five soil columns, each with a diameter of 8.7 cm and a height of 100 cm, were taken using a hammer-driven sampling cylinder to determine root distribution with depth. Each column was divided into ten samples, 10 cm high. In the laboratory, the soil was washed out from each sample and the weight of the roots determined.

Field experiments were carried out to determine the vertical continuity of macropores in the soil. Together with soil profile descriptions, tracer experiments were carried out. In September 1986, just after the first rains, a large quantity of a 0.1% solution of methylene blue in water was applied to the soil at two plots. In this way the walls of vertically continuous cracks and worm channels are stained by the dye. The upper 10 cm of the topsoil were removed before the experiment. Two hours after infiltration, the plots were carefully dug out and horizontal planes prepared at several depths down to 135 cm below the soil surface. Plastic sheets were placed on these planes and all walls of stained macropores marked with a pen. These drawings were later analysed using the electro-optical image analyser Quantimet 970 (Jongerius et al., 1972).

Another field experiment was done to verify the hypothesis about bypass flow and internal catchment. Small soil cores were taken at intervals of 5 cm depth, down to 150 cm below the soil surface in a 1 m^2 plot. Subsequently, 1 cm of water was applied to the plot and new cores were taken after 25 min. Then, 1 cm of water was applied again and the last set of cores taken after another 25 min. Volumetric moisture contents were determined in the laboratory. During the growing season of 1986, moisture samples were taken at different dates.

Experiments using soil columns

To measure bypass flow, fifteen undisturbed soil columns from 0–20 cm depth were sampled in PVC cylinders (diameter 20 cm) in five clusters of three columns scattered over the experimental plot, using the techniques described by Bouma et al. (1981). These columns were air-dried for two weeks to a pressure head of approximately $h = -1000$ cm, as derived from measured volumetric moisture contents and moisture retention curves. In order to prevent boundary flow between the soil columns and the PVC cylinders, large quantities of grease were applied but this was ineffective, as evidenced by staining tests. PVC rings around the remaining twelve soil columns were therefore removed and columns placed in bottomless buckets. Gypsum was poured into the space between the soil and the wall of the bucket, to obtain a tight contact and to eliminate boundary flow. This assembly was placed on a perforated disc fitted into a funnel as described by Bouma et al. (1981).

Using a rain simulator (Morin et al., 1966), subsequent rains of two intensities were created, 20 and 35 mm h^{-1}, respectively. When applied for 50 and 25 min respectively, these quantities (called first and second rain shower) have a probability of occurring about twice a year under Dutch conditions (Buishand and Velds, 1980). Methylene blue powder was applied to the soil surface before each shower to allow staining of continuous voids. The quantity of water collected from the columns was measured several times during and after rain application. Thus, inflow and outflow graphs could be produced. Weights of all constituent parts were recorded before and after the experiments. Weights of the soil columns were recorded after each rain when drip-

TABLE 1

Representative measured moisture retentions (first record) and hydraulic conductivities in cm d^{-1} (second record) at some pressure heads h for a clay loam grassland soil

Depth (cm)	h (cm)							
	0	−10	−50	−100	−500	−1000	−10000	−16000
5–25	0.54	0.57	0.49	0.46	0.37	0.25	0.15	0.13
	50	0.6	5×10^{-2}	2×10^{-2}	3×10^{-3}	1.4×10^{-3}	8×10^{-5}	5×10^{-5}
26–46	0.42	0.40	0.38	0.37	0.32	0.12	0.08	0.07
	250	3.0	1×10^{-2}	4×10^{-3}	1.1×10^{-3}	4.0×10^{-4}	1.5×10^{-5}	1.0×10^{-5}
75–95	0.43	0.42	0.40	0.38	0.30	0.24	0.14	0.13
	999	1.0	1×10^{-2}	4.5×10^{-3}	1.3×10^{-3}	1.0×10^{-3}	7×10^{-3}	5×10^{-5}

ping of the soil columns had stopped. After applying both rains, drawings were made of the stained voids of three columns at a depth of 19 cm.

After careful wetting of the entire soil columns to a pressure head of approximately −200 cm, as derived from measured volumetric moisture contents, the two rain intensities were again applied (third and fourth rain shower) on the remaining nine soil columns. Three additional soil columns were used for making drawings of the stained voids. Finally all soil columns were oven-dried to obtain average volumetric water content and bulk density.

Simulation model

The transient one-dimensional finite difference simulation model ONZAT (Van Drecht, 1983) was used to calculate soil water regimes for the year 1986. This model is derived from the SWATRE model (Belmans et al., 1983). It calculates (among other things) pressure heads, moisture contents and air-filled porosities as a function of depth and time. Actual evapotranspiration is also calculated. The upper boundary condition is defined by daily rainfall and potential evapotranspiration, the lower boundary condition by water table levels. Input data, specially measured for this study, comprise $h(\theta)$ and $K(h)$ relations, root distribution, water table levels and bypass flow data. Measurements of physical properties were made sixfold per soil horizon. Some representative data are listed in Table 1.

A subroutine simulating bypass flow was added to the model. Bypass flow only occurs during heavy rains, so a threshold value for daily rain was introduced. In this study, a value of 0.7 cm d^{-1} was used, which implies the occurrence of bypass flow for one out of every ten rain days. Bypass will occur only when this value is exceeded. Bypass water is assumed to infiltrate at the depth where internal catchment occurs, as derived from the morphological analysis described above. The pressure head of the topsoil influences the quantity of bypass flow by a function shown in Fig. 1. This function was derived experimentally by measuring bypass flow in 9–12 soil columns at two different

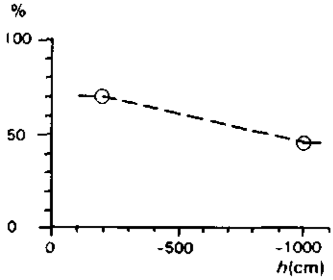

Fig. 1. Percentage of daily rainfall (> 0.7 cm d^{-1}) that will bypass as a function of the soil pressure head (*h*).

pressure heads. In the model bypass water is injected at depths where internal catchment occurs, thereby reducing the quantity of rain infiltrating at the surface. In this study two depths apply (represented in the model by two nodes), 60 cm depth for the continuous cracks, and 135 cm for the worm channels. The relative quantity for each depth can be selected arbitrarily.

To facilitate calculations and to prevent pseudo-accuracy, the following simplifying assumptions were made:

(1) The quantity of daily rain now determines the occurrence of bypass flow. It would be more realistic to use rain intensities instead, but these data are not available.

(2) If bypass flow occurs, it is assumed that all water moves to 65 cm (cracks) and/or 135 cm (worm channels). It is assumed that no water is absorbed laterally by the soil during downward flow. This is correct for heavy clay soils (Hoogmoed and Bouma, 1980) but not so realistic for the soil being studied here, as will be explained later.

RESULTS

Field studies

The measured root distribution shows that 88% of the roots (by weight) are found in the upper 10 cm, and more than 95% within 20 cm. Single roots were observed to a depth of 50 cm. Root activity in the model was therefore assumed to decrease sharply below 20 cm and to end at 50 cm. The root activity function used in the simulation model was developed by Hoogland (Hoogland et al., 1981).

Field sheets of stained voids to a depth of 140 cm (Fig. 2) were scanned by Quantimet to provide a quantitative measure for the length per unit horizontal cross sectional area of continuous, stained voids (Fig. 3). No distinctions were made between worm channels and cracks. Additional field observations showed the occurrence of stained worm channels to a depth of 135 cm below the surface. Cracks did not extend into the loamy subsoil beyond 60 cm depth. Thus, there are two systems to be considered: continuous cracks between

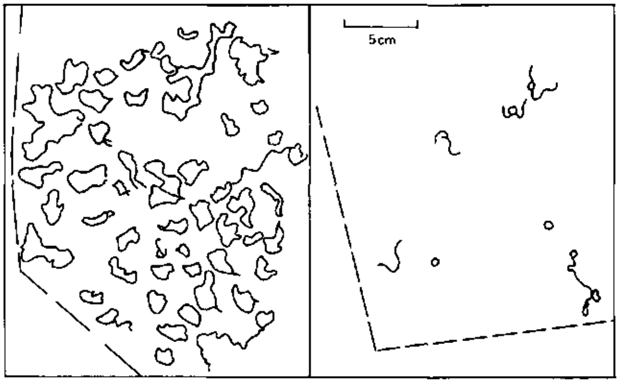

Fig. 2. Stained walls of cracks and worm channels at horizontal cross sections at depths of 17 cm (left) and 58 cm (right).

structural elements only occurring in the top 60 cm (Fig. 4), and worm channels that extend from the soil surface to 135 cm depth.

Results of water applications and subsequent soil sampling are presented in Fig. 5. Pressure heads were derived from volumetric moisture contents and moisture retention data. Significantly higher pressure heads were observed at depths of 60 and 135 cm below the surface following the application of water.

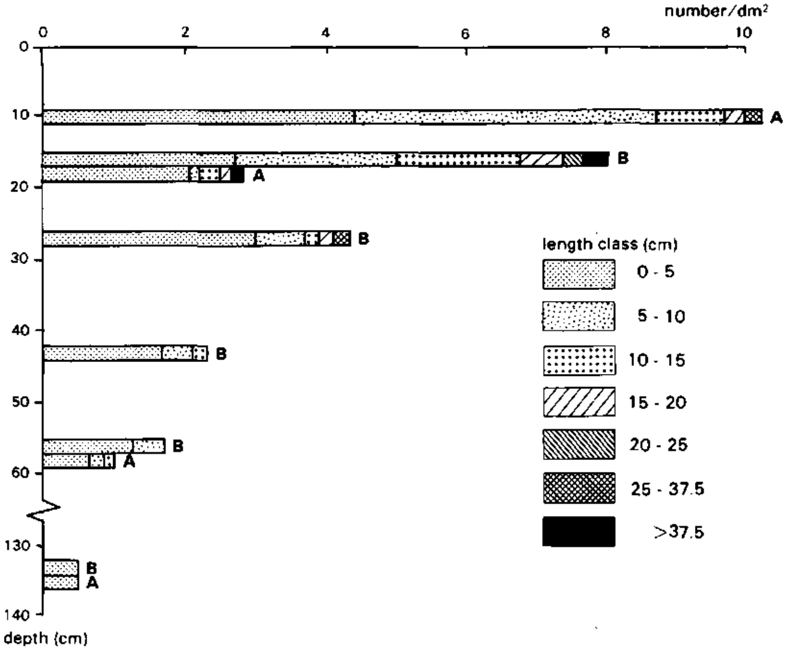

Fig. 3. Number and length of walls of stained voids and channels in horizontal cross sections at different depths. Drawings were made in the field. The letters *A* and *B* refer to different plots.

Fig. 4. Patterns of water movement along vertical natural ped faces in a clay loam soil as indicated by methylene blue.

This observation is in agreement with the morphological data which suggested internal catchment at depths of 60 and 135 cm. Higher pressure heads at 60 and 135 cm would not occur when ignoring bypass flow and internal catchment. This aspect was proved by running the simulation model assuming only Darcy-type unsaturated flow. Results in Fig. 5 show that the wetting front would then only have penetrated to depths of about 7 and 12 cm after the first and second water application, respectively.

The slight increase in observed pressure heads between 20 and 50 cm depth after the application of water (Fig. 5) suggests that some lateral absorption occurs. As mentioned earlier, this is not included in the simulation model. It could be included, if so desired, by incorporating the submodel proposed by Hoogmoed and Bouma (1980).

Laboratory experiments

Results of the bypass flow experiments are summarized in Fig. 6. The initial pressure head before the first rain shower was approximately −1000 cm and increased to approximately −400 cm after the first two rains. These pressure heads, however, are averages for the entire column. Pressure heads will be higher in the surface layers as well as near macropores. Before the third rain shower, pressure heads were approximately −200 cm, increasing to approximately −100 cm after the fourth rain. Pressure heads were derived from measured volumetric moisture contents and moisture retention data (Table 1). Outflow of free water from unsaturated soil results from bypass flow. This

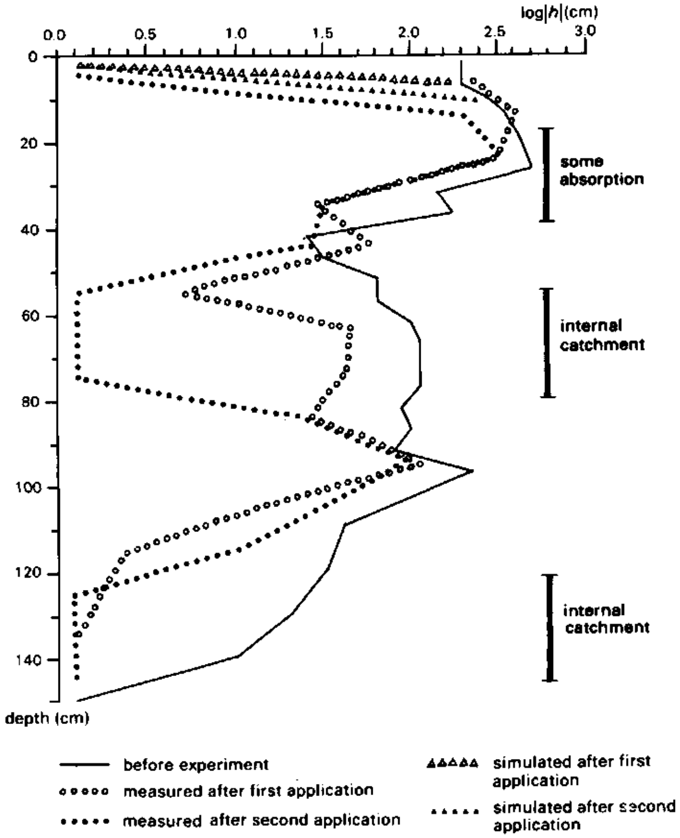

Fig. 5. Measured and simulated pressure heads as a function of depth before and after two applications of water.

phenomenon is well demonstrated by staining in the column, as shown in Figs. 2 and 4. The water follows continuous cracks, as indicated by staining, bypassing the major part of the soil.

To compare results obtained here with those obtained by Darcy-type unsaturated flow following surface infiltration, model calculations were made for soil columns with an initial pressure head of -1000 cm using the applied rain regime. The model would indicate no outflow at all, and the wetting front would penetrate only to depths of 6 and 15 cm after the first and second rain shower respectively.

In our experiment, all the water leaving the soil columns during the first two showers was blue. However, uncoloured water left some soil columns during the third shower, even though outflow started within a few minutes after the start of the rain. According to Darcy simulation of water flow in the soil columns, this rapid outflow is impossible, because the simulated infiltration front is about at the bottom of the soil column (20 cm depth) after the applica-

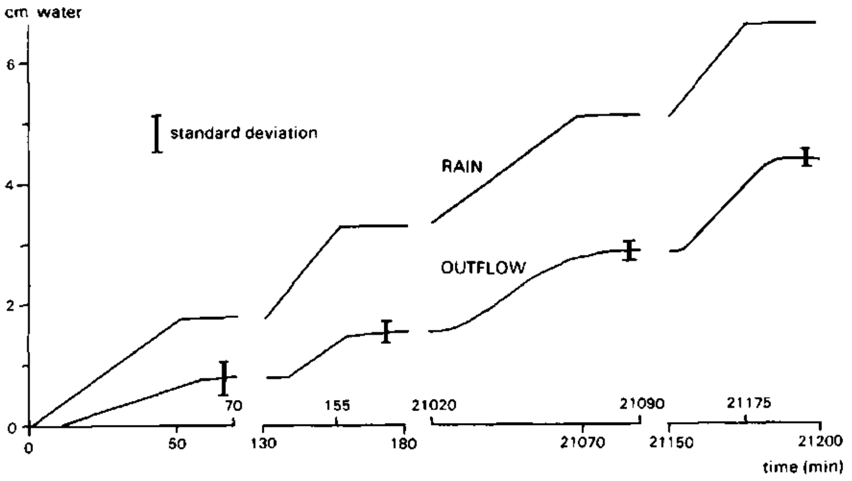

Fig. 6. Measured inflow and outflow rates of four rain showers. Mean outflow and standard deviation of outflow after each shower as determined in 15 large undisturbed soil columns.

tion of the third rain shower and simulated outflow is still almost nonexistent. Measured outflow, therefore, must be the result of water bypassing the major part of the soil. But, contrary to the first and second showers which resulted in the outflow of coloured water only, some displacement of uncoloured water must have occurred during the third shower before coloured water appeared. During the fourth shower water inflow equalled outflow, indicating saturated flow conditions in the soil. Here, displacement of water in the soil rather than bypass flow had become the dominant process. Simulation confirms this flow condition. Because of this, calculations for bypass flow (Fig. 1) were not based on the fourth shower.

Results from the model

The simulation model was applied to field conditions, using weather data for 1986. Available measurements of soil water contents during this year were inadequate to thoroughly validate the model. Exploratory runs were made to estimate the relative importance of bypass flow and internal catchment in calculating real evapotranspiration and the water balance for an entire growing season. These estimates will be used to focus further field research.

Simulated evapotranspiration from January to October 1986 for different flow conditions is shown in Fig. 7. Results of Fig. 7 (line A) are based on an application of the classical model ignoring bypass flow and internal catchment. Water deficits would occur in August (between days 210 and 230), reaching a total of about 25 mm. Results in Fig. 7 (line B) are based on a consideration of bypass flow and internal catchment assuming that half of the bypass water flows into the cracks and the remainder into the worm channels. The calculated water deficit would occur in July and August (between days 180 and

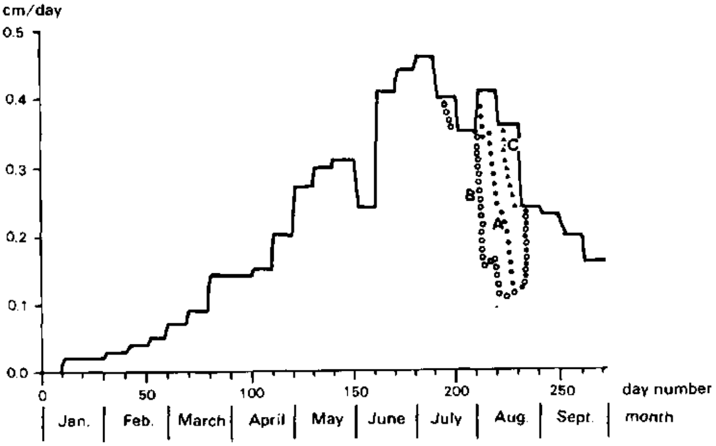

Fig. 7. Simulated evapotranspiration in 1986 for different flow conditions: *A* ignoring bypass flow and internal catchment; *B* bypass flow, 50% into the cracks and 50% into the worm channels; and *C* bypass flow, 100% into the cracks. The solid line represents potential evapotranspiration.

230), reaching a total of about 50 mm, which is significantly higher than the 25 mm obtained with the classical model. The water deficit would even reach 65 mm when assuming that bypass water flowed only into the worm channels. This situation, however, is considered to be rather unrealistic. Interesting conditions arise when assuming 100% bypass flow into the cracks (Fig. 7, line C). Then, the water deficit would only be about 5 mm, which is significantly lower than the value obtained when ignoring bypass flow. At first sight this result is surprising because bypass flow in heavy clay soils resulted in loss of water to the subsoil and therefore in higher soil-moisture deficits when compared with conditions where bypass flow was ignored (Bouma and De Laat, 1981). In the present case, however, water accumulates at 60 cm depth. Upward unsaturated flow to the grass roots is possible from this depth, in view of prevailing hydraulic heads in the growing season and the good hydraulic conductivity of the clay loam. In fact, assuming 100% bypass flow into cracks not deeper than 60 cm would result in a more effective wetting of the *total* root zone in these clay loam soils. Plants get water not only from rain wetting the soil surface, but also from subsurface soil layers moistened through the cracks. Thus, transpiration will increase as compared with the situation without bypass flow, when water is only present in the upper 10 cm of the soil.

DISCUSSION

This study demonstrates the importance of bypass flow in soils other than heavy clay soils. Bypass flow has been discussed here only in the context of the soil-water regime. The phenomenon is, however, also important when considering the vertical movement of dissolved substances, such as fertilizers and pesticides (e.g. Dekker and Bouma, 1984). Bypass flow and internal catchment should, therefore, be considered when studying displacement of solutes in clayey soils, as such movements may be strongly affected. The concept of internal catchment, introduced in this study, is relevant for field conditions common in alluvial soils with cracking upper layers and noncracking, more sandy, subsoils. Internal catchment is still more relevant under arid conditions where evaporation rates are high. Here, infiltration by bypass flow and internal catchment is very attractive for water conservation, but only so if the resulting moistening of the subsoil occurs within or just below rooting depth.

ACKNOWLEDGEMENTS

Permission granted by W.P. Spaan of the Agricultural University of Wageningen to use the rain simulator and the cooperation of D. Schoonderbeek (Quantimet measurements) are gratefully acknowledged.

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10 IMPACT OF SOIL MANAGEMENT SYSTEMS ON SOIL STRUCTURE AND PHYSICAL PROPERTIES IN A CLAY LOAM SOIL, AND THE SIMULATED EFFECTS ON WATER DEFICITS, SOIL AERATION AND WORKABILITY

Submitted for publication in Soil & Tillage Research

Impact of Soil Management Systems on Soil Structure and Physical Properties in a Clay Loam Soil, and the Simulated Effects on Water Deficits, Soil Aeration and Workability

H.A.J. VAN LANEN[1], G.J. REINDS[1], O.H. BOERSMA[1] and J. BOUMA[2]

[1] *The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen (the Netherlands)*

[2] *Agricultural University, Department of Soil Science and Geology, P.O. Box 37, 6700 AA Wageningen (the Netherlands)*

ABSTRACT

The effects of different soil management systems on soil structure and associated physical properties in a Dutch clay loam soil were evaluated using a combination of simulation modelling, field investigations and laboratory experiments. The investigations were focused on field recognition of identical soils only differing in soil-structure type caused by soil management systems. Two soil-structure types were recognized: a type developed in permanent grassland and a type in young arable land, which had been used for intensive vegetable-growing since 1979. The types were characterized by examining the micro- and macro-morphology and soil hydraulic properties, such as soil structure, rooting patterns, pore-shape and -size distribution, bypass flow and water retention and unsaturated hydraulic conductivity characteristics. Field recognition of structure types and subsequent morphological and physical characterization was used as an alternative to the application of a machine-plant submodel.

Significantly different properties of both soil-structure types were functionally interpreted by using a simulation model for the soil-plant subsystem. Morphological and hydraulic analyses were essential for the definition of proper boundary conditions and input parameters. The land qualities water deficits, workability and soil aeration, were calculated for a potato crop under Dutch climatological conditions. Expressions for temporal variability were obtained by using a 30-year record of weather data. The soil structure of permanent grassland proved to be more favourable than that of young arable land. This resulted in a 10% decrease in the average annual water deficit, 40% more workable days in the planting phase and 5% to 10% more days with a well-aerated soil. The impact of these differences on the potato tuber yield interpreted in terms of the effect of soil-structure degradation, was estimated to be at least 5% per cent in 20 out of 100 years under Dutch climatic conditions. The differences calculated also equalled the maximum possible effect of soil-structure regeneration.

INTRODUCTION

In the past two decades root and field vegetable crops superseded cereals as the dominant crops in the Netherlands, detrimentally affecting the soil structure of Dutch arable land. This soil-structure degradation is chiefly due to a later harvest, usually under wetter soil conditions, and production and field transport of more tonnes of harvestable products. Despite a considerable research effort, quantitative knowledge about interactions between mechanisation, soil conditions and crop growth, is as yet insufficient (e.g. Boone, 1988; Håkansson et al., 1988). Continuous research is needed to investigate the highly complex machine-soil-crop system. One way of expanding know-how would be by conducting field experiments. These experiments, however, are too expensive to cover the whole range of prevailing crops, soil and weather conditions and the different field traffic and tillage actions. Hence, a combination of field experiments and simulation modelling could be an attractive alternative to extrapolate the experimental results obtained at one site to a wider range of site conditions.

The current models that simulate the total machine-soil-crop system, have serious shortcomings (e.g. Gupta and Allmaras, 1987; Hadas et al., 1988). An accurate prediction of soil structure and a quantification of soil pore geometry and associated physical properties, after using a tillage implement, is impossible. Although the comprehensive models are not yet operational, validated segments, such as the machine-soil submodel and the soil-plant submodel, may be applied. For instance, field measurements of physical characteristics and the use of a soil-plant simulation model to investigate water-associated effects of different soil management systems have been put in practice by Van Lanen et al. (1987), Simota and Canarache (1988) and Van Lanen and Boersma (1988).

Our study set out to quantify the effects of different tillage and field traffic systems on land qualities, such as water deficit, workability and soil aeration for soil-structure types in clay loam soils. Two soil-structure types were considered: (G) permanent grassland; (A) young arable land used for market gardening. These structure types occur in otherwise identical soils, being a result of different soil management systems. We investigated the effects of relatively recent changes in soil structure. Differences in simulated land qualities and crop yields provided quantitative and functional information on soil-structure degradation caused by different soil management systems. Any positive effects of soil-structure regeneration were also explored. More details on our study were provided by Reinds (1988a). Results for sandy loam soils under Dutch climatic conditions were reported by Van Lanen et al. (1987) and Van Lanen and Boersma (1988).

METHODS AND MATERIALS

Soils, soil-structure types and physical properties

Clay loam soils cover about 190,000 ha in the Netherlands. The clay loam soils considered in our study were located near Piershil, about 15 km south of Rotterdam. The soils had developed in calcareous, young marine deposits and were classified as Typic Fluvaquents (Soil Survey Staff, 1975) and as Calcaric Fluvisols (FAO-UNESCO, 1974). The clay content of the topsoil was about 30% and decreases with depth to about 18% at 1 m below soil surface. The organic matter content and the pH of the topsoil were 2.4% and 7.5, respectively. More analytical data have been provided by Van Lanen and Boersma (1988) and Reinds (1988a; 1988b). The soils were well drained. The mean highest water table (MHW) was at a depth of 60-70 cm and the mean lowest water table (MLW) at 160-180 cm below the soil surface (Van der Sluijs and De Gruijter, 1985). In the Netherlands, soils such as these are mainly used to grow arable and field-vegetable crops. Such small areas can be found in permanent grassland in the vicinity of farms.

Two different soil-structure types in clay loam soils were considered in our study, i.e. a soil-structure type developed in permanent grassland (G) and a type developed in young arable land (A). Until 1979 both soils were identical and had been used as permanent grassland for decades, when the land which with soil-structure type A was changed from permanent grassland to land for market gardening. The experimental sites with the different soil-structure types were adjacent plots, less than 100 m apart. In the period 1985-1988 field and laboratory experiments were conducted to characterize both soil-structure types. The structural features of the two types is presented in Figure 1. The structure description of type A holds for the situation in 1987, while the one for G applies to any time. During the experimental period, the perennial vegetable crop rhubarb was grown on young arable land, after 6 years of very intensive vegetable-growing of usually more than one crop per year. The notable differences in soil structure of the topsoil were clearly visible in the field, as illustrated in Figure 2. Soil-structure was further characterized in the laboratory by the electro-optical image analyses, using thin sections (Kooistra et al., 1984; 1985). The pore geometry was described in terms of pore shape and size.

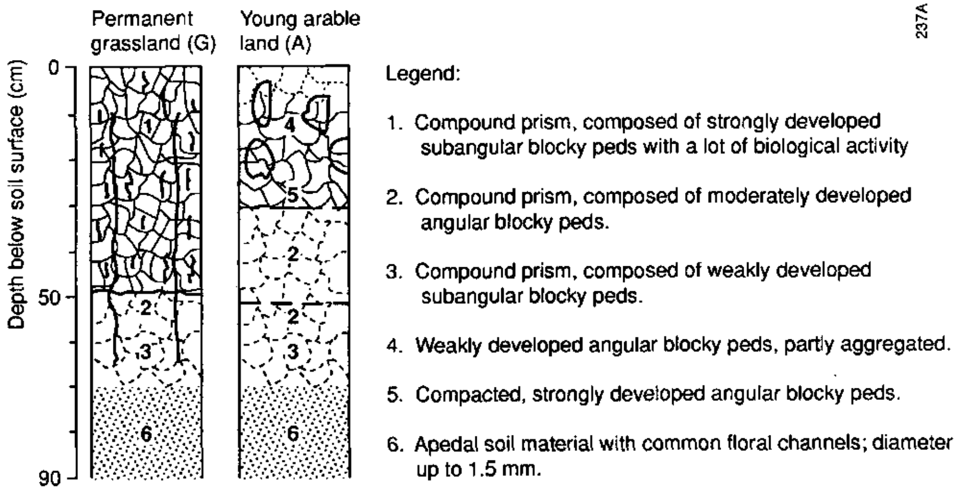

Fig. 1 Schematic description of two soil-structure types, G and A, developed in a clay loam soil.

Because differences in pore morphology could affect physical properties of the soil, the water retention and unsaturated hydraulic conductivity curves were measured using undisturbed soil samples from each soil-structure type. The samples were gathered at three depths, i.e. the topsoil (0-25 cm), an intermediate layer (25-45 cm) and the subsoil (>55 cm). The samples were taken in five- or sixfold. The samples of the permanent grassland site had been collected in 1985. The young arable land was sampled in 1987 after the ploughed topsoil had sufficiently settled following planting of the rhubarb crop. Thus, morphological and physical properties of young arable land apply to the situation eight years after the change from permanent grassland to land for market gardening. Water retention (θ-h) and hydraulic conductivity (K-h) curves were measured in the laboratory using conventional and new techniques (Bouma, 1983; Kooistra et al., 1984; 1985; Reinds, 1988b; Van Lanen and Boersma, 1988).

In clay loam soils, free water may move vertically downwards through macropores along an unsaturated soil matrix (bypass flow). The bypass flow was measured in undisturbed soil samples (height and diameter 20 cm) under a rainfall simulator (e.g. Van Stiphout et al.,

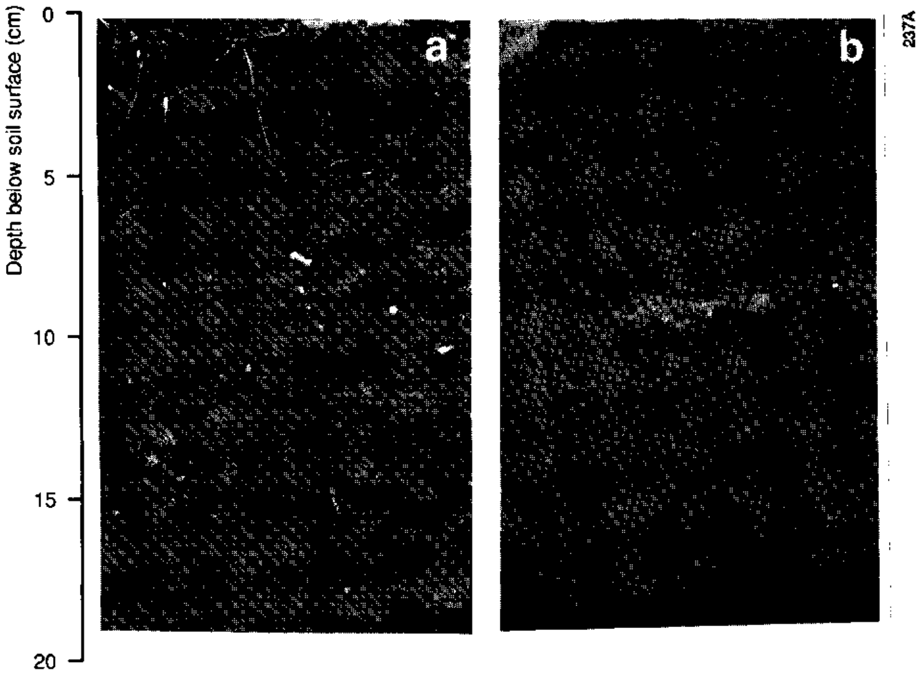

Fig. 2 The upper 20 cm of two soil-structure types occurring in a clay loam soil. a: permanent grassland type; b: young arable land type.

1987). Because bypass flow is a function of the water content of the soil, the measurements were repeated for various field water conditions to derive relationships between daily rainfall, bypass flow and soil water content. Consequently, in May and June 1987 and in February 1988, both soil-structure types were sampled in threefold. Each of the soil-structure types produced significantly different relationships, as reported by Van Lanen and Boersma (1988). The depth of infiltration of bypass flow into the soil matrix of the subsoil ('internal catchment') had been measured in field experiments conducted on permanent grassland (Van Stiphout et al., 1987). Subsurface infiltration occurred mainly at the base of the cracks (transition of the clay loam topsoil into the sandy loam subsoil) at about a depth of 60 cm and at the base of worm channels at about a depth of 135 cm. Observations showed that worm channels in young arable land were predominantly discontinuous in the topsoil due to superficial tillage operations (Fig. 1). Therefore, bypass flow in young arable land was assumed to infiltrate only at the base of the cracks at about 60 cm depth.

Simulation model

Description

The soil-plant model (ONZAT) used had been proposed and validated by Van Drecht (1983; 1985). The model is based on principles of the SWATRE model (Belmans et al., 1983;

Feddes et al., 1988b), which has been extensively validated for various crops, soils and climates (e.g. Van Wijk and Feddes, 1986; Hack-ten Broeke and Kabat, 1989). ONZAT simulates transient, one-dimensional, soil-water flow in a vertical direction. An implicit finite-difference technique is used to solve the partial, non-linear differential equation that describes unsaturated water flow. The model ONZAT has been extended with a submodel that describes bypass flow and internal catchment (Van Stiphout et al., 1987). Each soil layer (thickness 5-15 cm) must be characterized by soil-physical data (θ-h and K-h relationships), allowing for the definition of a layered soil profile. The model capability to define a layered soil also offers the opportunity of specifying depths to which bypass flow can infiltrate. Daily rainfall and potential evapotranspiration are used as upper boundary condition. Daily water-table depth or a relation between flux and the water-table depth are used as lower boundary condition of the soil profile. Water uptake by plant roots may occur from an increasing number of soil layers, corresponding with an increasing rooting depth of annual crops. Actual water uptake, which equals actual evapotranspiration, depends on the potential crop evapotranspiration, the rooting depth and the soil-water pressure head distribution in the root zone. A sink term as reviewed by Feddes et al. (1988a; 1988b) governs the water uptake. The sink term defines the volume of water taken up by the roots per unit bulk volume of the soil per unit time as a function of evaporative demand and the pressure head. Clods formed by soil management operations and natural dense soil aggregates may cause a heterogenous root distribution and very steep soil-water pressure head gradients inside the soil-structure elements. These effects on crop water uptake can be incorporated in the sink term by specifying the relative volume of readily accessible water in the clods or aggregates as proposed by Bouma and Van Lanen (1989).

The pressure heads, water contents and air-filled porosities as a function of depth and time simulated by the simulation model ONZAT are of particular interest in the calculation of the land qualities. More information on the principles of the model have been provided by Van Drecht (1983; 1985), Van Lanen et al. (1987) and Van Stiphout et al. (1987).

Validation

The simulation model ONZAT was validated for the soils considered, using data measured in 1987. Validation was necessary to check the reliability of the model for application in our study. In 1987, grass and rhubarb were grown on the soils with a soil-structure type of permanent grassland and young arable land, respectively. Measured groundwater depth on the experimental field and meteorological data from a nearby station were used. Potential evapotranspiration of both the grass and rhubarb crop were estimated using open-water evaporation and crop coefficients (e.g. Doorenbos and Kassam, 1979). The crop coefficients of the rhubarb crop consisted of the pronounced seasonal variation of crop height and soil cover and the early harvest. Bypass flow was derived from the measured relationships for both soil-structure types as reported by Van Lanen and Boersma (1988). Rooting depth findings for permanent grassland were provided by Van Stiphout et al. (1987). The depth and distribution of rhubarb roots on young arable land were determined on a carefully prepared wall of a soil profile pit by using a transparent foil technique (e.g. Kooistra et al., 1985). Rooting patterns of the rhubarb crop and shapes and sizes of the soil peds were carefully analyzed to ascertain whether the roots had poor accessibility to water.

Volumetric water contents at different depths and dates were measured to validate the model ONZAT, as illustrated in Figure 3. Because of the variability in measured hydraulic properties and uncertainties, such as crop transpiration coefficients and harvest date (Reinds,

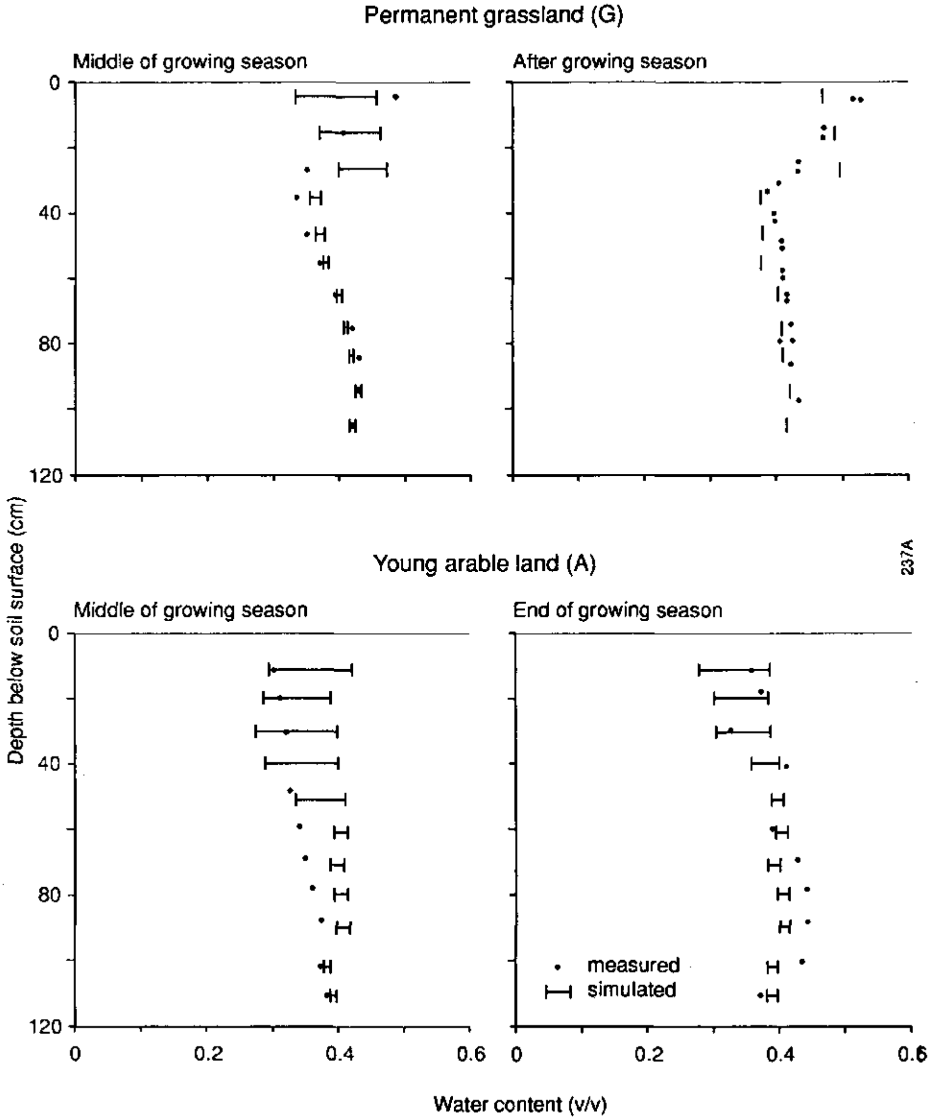

Fig. 3 Validation of the simulation model ONZAT comparing measured and simulated range of water contents in two soil-structure types developed in a clay loam soil.

1988a) a range in simulated water contents had to be distinguished. The range was obtained by running ONZAT several times. A set of parameters was chosen each run to fit the physical limits relevant to the considered experiments. The modification of the parameters hardly affected the simulated moisture contents for permanent grassland after the growing season. Thus, no range has been presented for this date. The simulated water contents corresponded reasonably well with the measured data. The coefficient of variance (VC) was used as a quantitative measure for the deviation between measured water contents and simulated water contents. The VC between measured and simulated water contents varied from 0.05 to 0.16. The VC was mostly between 0.08 and 0.1 (Reinds, 1988a).

Application of the model to derive land qualities

After satisfactory validation, the land qualities were simulated for both soil-structure types. The simulations were made for the period 1955-1984 using meteorological data from a station operating in the south-west of the Netherlands. It thus enabled probability estimates to be provided for the various land qualities of both soil-structure types, taking into account the temporal variability caused by the prevailing weather conditions. Potatoes were assumed to grow on both soil-structure types because of their relative importance in terms of net revenues for the Dutch arable farmer. This somewhat hypothetical situation for the permanent grassland soil-structure type was used to illustrate the possible effects of soil-structure differences. Potential evapotranspiration, water extraction by the potato roots and water table depth were approximated as described by Van Lanen et al. (1987). Rooting depths in both soil-structure types were taken to be equal to those of unrestricted potato root growth in sandy loam soils (e.g. Boone et al., 1985). Potatoes grown on both soil-structure types were assumed to have a dense and homogeneous rooting pattern as demonstrated by the rhubarb crop.

Land qualities

The land qualities water deficit, workability and soil aeration for both soil-structure types in clay loam soils were determined according to the proposal by Van Lanen et al. (1987). Simulated data of the actual daily evapotranspiration, and of the pressure head and the air-filled porosity of the topsoil were of particular significance in deriving the land qualities.

Water deficit over a certain period of time (e.g. total growing season) was defined as the cumulative difference between the potential and actual evapotranspiration, as calculated on a daily basis by ONZAT.

Workability was derived from a soil- and crop-specific threshold value (workability limit) and the simulated pressure heads at 5 cm depth. If the pressure head in the topsoil of a clay loam soil is below a threshold value of h= -70 cm, moderate to good field conditions for potato planting should prevail (Van Wijk and Feddes, 1986). However, on days with a pressure head higher than the threshold value, planting cannot be accomplished without damaging the soil structure. A Boolean approach was followed, resulting in an adequate or an inadequate workability for each day. The probability of occurrence of a workable day in a certain period was determined by analysis of the simulated number of workable days in that particular period during the years 1955-1984.

Simulated air-filled porosity in the topsoil was taken as the indicator for *soil aeration*. According to Bakker et al. (1987), if the air-filled porosity in clay loam soil was below a threshold value of 0.09 $m^3.m^{-3}$, soil aeration was considered to be insufficient. Consequently the diffusion coefficient of oxygen and carbon dioxide as well as the exchange of these gasses between the soil and the air was low. The occurrence of days with adequate soil aeration was determined by comparing the simulated air-filled porosities with the soil-specific threshold value. Probability occurrence of days with sufficient aeration was calculated using a similar Boolean approach as done for workability.

Eventually, simple crop growth models were used to estimate the effect of the land qualities on crop yield. Therefore, differences in soil-structure types due to soil management systems were converted to impact on crop yield, providing a further quantification of soil-structure degradation.

RESULTS

Soil structure and soil physical properties

Intensive tillage and traffic operations during eight years caused significant differences in the volume fractions of different pores. Both pore shape and size had been affected, as shown in Figure 4. Moreover in the lower part of the topsoil (10-30 cm) total macro-porosity (volume fractions of different pores >30 μm) was substantially higher in the permanent grassland type

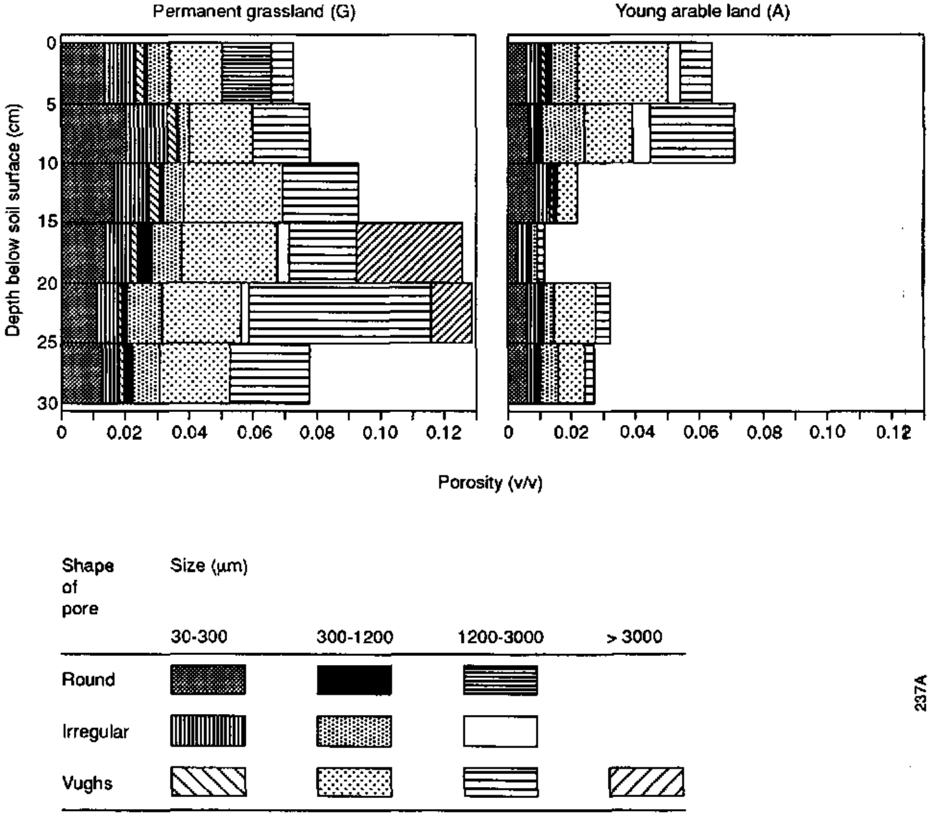

Fig. 4 Volume fraction of pores (> 30 μm) distributed over different pore-shape and three pore-size classes for two soil-structure types in a clay loam soil.

than in young arable land. Furthermore, the volume of round pores, representing worm activity, was considerably greater in permanent grassland.

Soil structure observations showed that because it was easy for the compound prisms or aggregates (Fig. 1) to be broken down to relatively small peds, no high mechanic resistances for root growth occurred. This was supported by the well distributed roots of the rhubarb crop observed. The dense and homogeneous rooting pattern and unsaturated hydraulic conductivity of these clay loam soils resulted in relatively high volumes of readily accessible soil water in the peds. Therefore, it was not necessary to adapt the sink term as proposed by Bouma and Van Lanen (1989), irrespective of the soil-structure type considered in our study.

Representative curves for soil water retention and hydraulic conductivity for the topsoil of both soil-structure types were derived of the individual samples (Fig. 5). The range of soil-water retention data of these individual samples at different depths has been presented by Van Lanen and Boersma (1988). Water contents in the topsoil of type G were up to log(-h) = 3.0, significantly higher than in type A. Above log(-h) = 3.0 the water contents of type A were slightly higher than those of type G. These differences in water contents indicated a higher available soil water in type G. The unsaturated hydraulic conductivities of the topsoil of type G were clearly higher than the ones of type A with the exception of the range of pressure heads close to saturation. Generally, these conductivity differences offer better conditions for up- and downwards flow of soil water in type G.

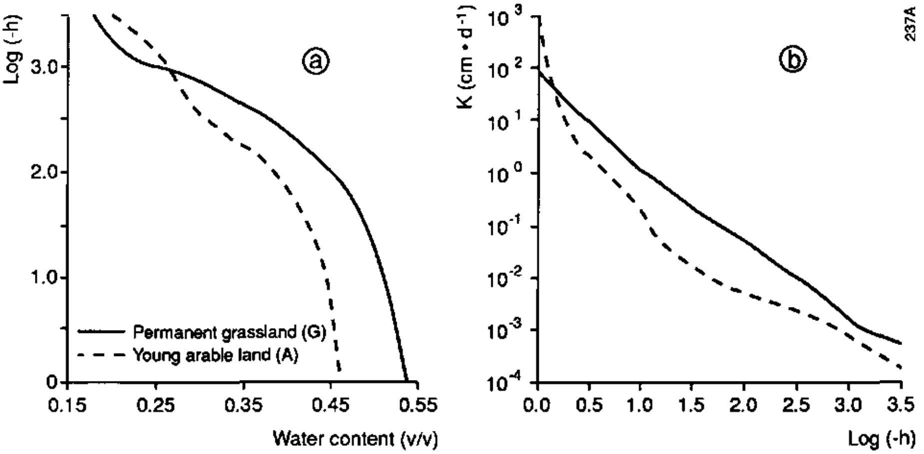

Fig. 5 Representative soil-water retention (a) and hydraulic conductivity curve (b) of the upper 25 cm of two soil-structure types developed in a clay loam soil.

After eight years of different soil management only slight changes occurred in the subsoil revealing minor differences between physical data of the subsoils of the two soil-structure types (Table I and Reinds, 1988b). At a depth of 40-50 cm, the total macro-porosity of type A was somewhat less (> 1%) than the porosity of type G, probably indicating the beginning

TABLE 1 Total macro-porosity of pores greater than 30 μm in the subsoil of the two soil-structure types in identical clay loam soils.

Depth below soil surface (cm)	Porosity as volume fraction	
	Permanent grassland	Young arable land
30-40	0.080	0.085
40-50	0.092	0.079
50-60	0.095	0.086

of subsoil compaction. However, differences in macro-porosity of less than 1% at a depth 30-40 cm did not clearly support this supposition.

Land qualities

Water deficit

The susceptibility to drought of these clay loam soils is low under Dutch climatic conditions, irrespective of the soil-structure type. The simulated mean annual water deficit of potatoes grown on soils of a soil-structure type A was 36 mm, while on soils of type G the deficit was slightly lower, i.e. 32 mm. The small water deficit was unequally distributed throughout the growing season. For both soil-structure types differences between the potential and the actual evapotranspiration were mainly restricted to the period May 20 to June 20.

The somewhat higher susceptibility to drought of type A compared to G is expressed in Figure 6. In 90 out of 100 years the water deficit of potatoes grown on soils with type A is predicted to be less than 50 mm, while on soils with type G the deficit is predicted to be less than 40 mm.

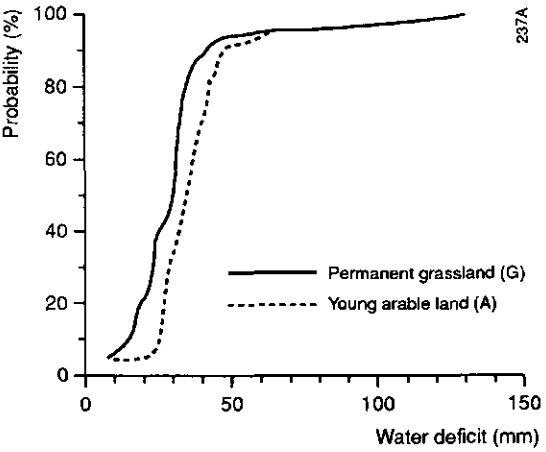

Fig. 6 Cumulative probability occurrence of annual water deficits of potatoes grown on two different soil-structure types of a clay loam soil.

The effect of water stress on yield is dependent on the phenological stage of the potato crop (e.g. Van Loon, 1981; Roth and Roth, 1985). In the growth stage after flowering, stress will certainly reduce tuber yield. In an earlier stage the effect depends on several aspects, such as the leaf area index, subsequent respiration losses and the possible change in the partitioning of the photosynthesis products. A small water stress in an early growth stage may even be beneficial for final tuber yield. According to a simple crop growth model proposed by the Werkgroep HELP (1987) a mean water deficit difference of 4 mm between both soil-structure types in these soils approximately equalled about 1.8% tuber yield difference.

Workability

The probability of a workable day for any day of the year relevant to field machinery work is indicated in Figure 7. In the Netherlands according to Alblas et al. (1987), the important periods for machinery work for potato growing are March 15 to April 30 (planting of potatoes) and June 15 to October 15 (harvesting of potatoes). Figure 7 was derived from simulated 24-hour data over a period of 30 years. The median probability of having a workable day on a soil with soil-structure type A was lower than that with type G (Fig. 7a). For instance, for half of the period the probability of occurrence of a workable day in mid-April would be less than 20% for soils with type A, whereas on soils with type G this probability would be about 50%. In September and October, the differences would be even more pronounced.

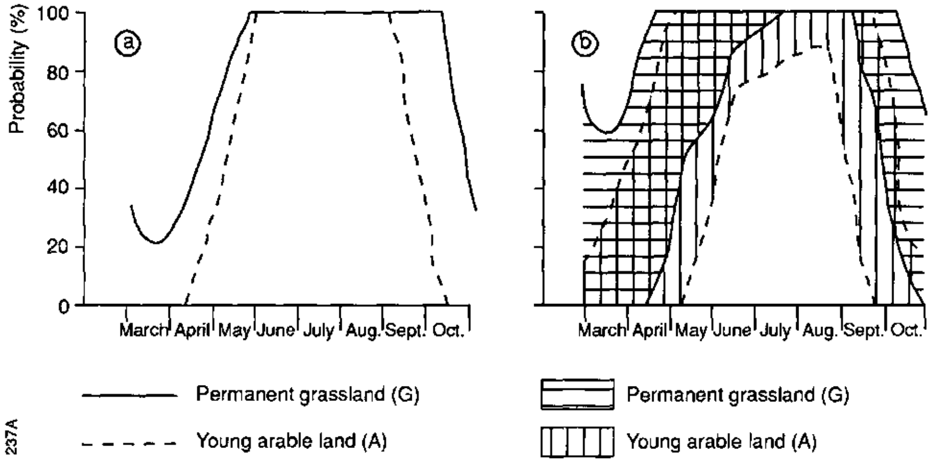

Fig. 7 Probability of occurrence of a workable day on two different soil-structure types of a clay loam soil. a: median; b: 10-90% prediction range.

The range in probability (10-90% prediction range) of occurrence of a workable day provides information on workability in eighty percent of the years (Fig.7 b). This range was derived from the earlier mentioned record of 30-year meteorological data. The probability ranges of both soil-structure types partly coincide (shaded area represented by squares).

Sections of the figure with only vertical lines imply that in those periods, in part of the period considered, the workability of soils with a soil-structure type A was worse compared to soils with type G. Conversely, only horizontal lines indicate a better workability in part of the considered years of soils with type G. For instance in mid-April, in eighty percent of the years, the probability of occurrence of a workable day was between 0% and 70% on soils with a soil-structure type A. For soils with a soil-structure type G the limits of the 80% probability range were higher in the same period, e.g. 5% and 95%. In September and October, the differences were more pronounced as already indicated by the median. For example, in mid-September, in eighty percent of the years it was possible for the probability of having a workable day to vary from 40% to 100% on soils with a soil-structure type A, while on soils with type G hardly any days occurred with inadequate workability.

A higher probability of occurrence of workable days results in the possibility of a longer growing season. Generally, a yield reduction of about 0.1% to 0.2% per day in April and 0.3% to 1.3% per day in May occurred when potatoes were planted after the optimal date (e.g. Witney and Elbanna, 1985). Workability restrictions were assessed to cause a potato yield depression of 2% or more in 50% of the years grown on soils of type G and in 70% of the years grown on type A. Yield differences of 5% or more were estimated to occur in 20 out of 100 years between both soil-structure types and differences of 10% or more in 10 out of 100 years.

Soil aeration

Soil aeration was derived from simulated 24-hour data of the air-filled porosity over a period covering 30 years. Because the air-filled porosity and workability are linked through the simulated pressure head and the soil water retention characteristic, similar graphs as Figure 7 can be produced for soil aeration (Van Lanen et al., 1987; Reinds, 1988a). Therefore in

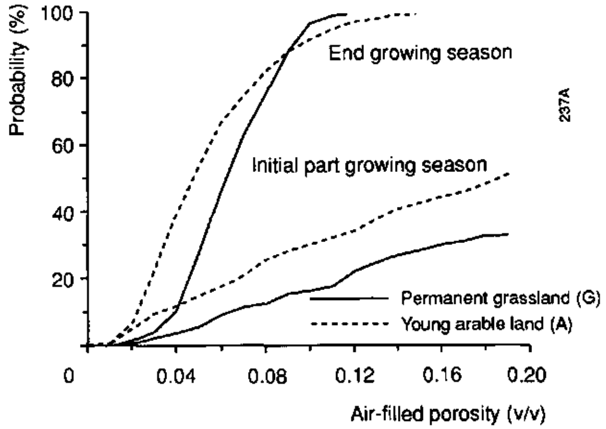

Fig. 8 Cumulative probability occurrence of air-filled porosities for two 10-day' periods (initial and final part of growing season) of two different soil-structures types developed in a clay loam soil.

Figure 8 the air-filled porosities for both soil-structure types are presented in a somewhat different manner. For example, in the second 10-day period of April, in about 50% of the years the air-filled porosity in soils with a soil-structure type A is predicted to be less than $0.05\ m^3.m^{-3}$, indicating unfavourable conditions for crop growth. In soils having type G this percentage equalled about 25%. In the initial part of the growing season, the threshold value of $0.09\ m^3.m^{-3}$, was exceeded only in about 10% of the years, irrespective of the soil-structure type. In the final stage of the growing season (September 1-10), the clay loam soils were better aerated than at the start. In soils with soil-structure type A, an inadequate soil aeration (air-filled porosity $< 0.09\ m^3.m^{-3}$) only occurred in about 30% of the years. The soils with the soil-structure type G were better aerated. An insufficient aeration only occurred in about 15% of the years. Therefore, in the first 10-day period of September there was a difference of 15%. The difference between both soil-structure types in per cent of years with an inadequate soil aeration are somewhat less in the major part of the growing season, e.g 5% to 10% in May to August (Reinds, 1988a).

The impact on the potato yield of soil aeration is difficult to assess because of direct effects (dry matter increase) and indirect effects (e.g. phytosanitairy problems). The estimated direct effect on these well-drained soils under average Dutch climatic conditions according to simple crop growth models is probably about a 2% difference in tuber yield between both soil-structure types. In about 50 out of 100 years the yield difference was assessed to be 2.5% or more between both soil-structure types and in 10 out of 100 years more than 5%.

CONCLUSIONS AND DISCUSSION

Intensive tillage and traffic operations on clay loam soils used for field-vegetable growing over a period of eight years resulted in significantly different soil-structure types as compared to otherwise identical soils used as permanent grassland. Different soil-structural types could clearly be recognized in the field and subsequently characterized in terms of macro- and micromorphological and soil hydraulic properties. Associated calculated differences in water deficits, soil aeration and workability prove the functional quality of the permanent grassland to be higher than that of the young arable land. A higher potato tuber yield of at least 5 per cent in 20 out of 100 years would be expected on Dutch clay loam soils with the favourable permanent grassland soil-structure as compared with the less favourable young arable land structure. These yield differences between the same soils with different soil-structures seem to be realistic given that similar or even more pronounced measured differences were reported by Van Loon and Bouma (1988) and Feddes et al. (1988a).

A prolonged application of the intensive soil management system on young arable land could be expected to result in a compacted subsoil, i.e. the formation of ploughpans. Under Dutch climatic conditions a disruption of ploughpans usually results in a more serious soil compaction after a few years (secondary ploughpans), as illustrated by Kooistra et al. (1985; 1986) and Van Lanen et al. (1987).

The results of our study can also be used to explore the maximum possible effect of soil structure regeneration by for instance, increasing the organic matter content, reducing root crops in the rotation and by implementing technical alternatives for current traffic and tillage systems, as suggested by Håkansson et al. (1988). If we assume that a soil-structure type of permanent grassland, as recognized in our study, is the most favourable soil structure, differences in water deficits, workability and soil aeration between a particular soil-structure and that of permanent grassland can be interpreted in terms of what farmers can theoretically attain. So, if in our case of clay loam soils, the soil structure of young arable land could be changed to the more favourable one of permanent grassland, then the maximum benefit to the farmer would be a 10% reduction in water deficits, 40% more machinery-work days in April and about 5% to 10% more days with an adequately aerated soil within the growing season.

Although comprehensive, integrated machine-soil-crop models still have serious shortcomings (e.g. Hadas et al., 1988), the results of our study show that submodels, such as the soil-crop model supplied with parameterized soil-structure types could be successfully applied to quantify negative effects of soil degradation and to explore possible positive effects of soil-structure regeneration. Moreover, the results could be used for a further development of the integrated model. Morphological characterization of soil structure form an integrated part of the procedure.

Simulation modelling combined with field experiments which have only been conducted for a few years enables us to extrapolate results to a wider range of site conditions. Effects of soil degradation may be transferred to a wide range of weather conditions by using a historical record of weather data, as shown in our study. Monitoring these effects on experimental fields during a long period to obtain similar temporal variability expressions, is nearly impossible because of budgetary restrictions. The introduction of simulation modelling in short-term conventional agronomic-tillage experiments in order to obtain a better understanding of experiments would be very attractive. This would allow us more opportunities to transfer knowledge to other agro-ecological conditions. Then, however, a prerequisite would be the collection of more soil physical data in addition to those such as penetrometer resistances, bulk densities, pore volumes and air-filled porosity at pF = 2.0.

On a farm scale, soil-structure types can reproducibly be recognized in the field by soil surveyors using macro-morphological techniques. Compared to conventional surveys, recognition of soil-structure phases on large-scale soil maps is invaluable to reduce variability within mapping units. Description and classification of soil structure do not need to be elaborated any further for this purpose, efforts should be concentrated on a further characterization of significantly different types by applying simple physical field tests, such as measurement of cone resistances, functional monitoring of soil water contents, pressure heads, gas concentrations, rooting patterns and analysis of infiltration experiments, possibly with tracers. Additionally, micro-morphological and soil physical analyses need to be made at the laboratory, as demonstrated in our study, to enable more realistic boundary conditions (e.g. soil-structure type dependent bypass and internal catchment) to be defined and to allow a more precise determination of parameters governing the flow processes in the soil. This knowledge is indispensable if realistic answers on current land use problems, which include soil management, crop production and environmental topics are to be provided.

ACKNOWLEDGEMENTS

We wish to thank Mrs. F. van de Veen for her contribution in measuring the physical properties. The results could not have been obtained without Mr. A.B. Schut (Piershil), who monitored water table depth and who permitted us to carry out the field experiments. We also thank Mr. D. Schoonderbeek for the electro-optical image analyses and Mr. W.P. Spaan (Wageningen Agricultural University) for the use of the rainfall simulator.

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PART III

11 QUALITATIVE AND QUANTITATIVE PHYSICAL LAND EVALUATION: AN OPERATIONAL APPROACH

SAMENVATTING

CURRICULUM VITAE

11 QUALITATIVE AND QUANTITATIVE PHYSICAL LAND EVALUATION: AN OPERATIONAL APPROACH

The different physical land evaluation methods from the previous chapters are summarized in the following. The differences between the evaluation methods in the context of the question being posed are described. Furthermore the specific role of the land characteristic 'soil macrostructure' in quantitative evaluation on farm scale is described.

In this part of the thesis it seems also appropriate to discuss lacking elements in the current physical evaluation methods. Major lacking elements are, for instance, environmental aspects and spatial variability. Some solutions are explored. Physical land evaluation usually cannot stand alone. Therefore, its place in integral land evaluation and the possible contribution to land use planning are discussed at the end.

11.1 PHYSICAL LAND EVALUATION METHODS

Different technical procedures can be used in physical land evaluation as shown in Chapters 3 to 10 inclusive. Because of the different type of results, the simple evaluation methods were described as qualitative evaluation methods and the more complicated methods were indicated as quantitative ones. These procedures are described in the following. Differences in terms of input and output are dealt with.

In this thesis a clear distinction was assumed between qualitative and quantitative physical land evaluation methods. In practice, however, various kinds of intermediate procedures can be used.

11.1.1 *Qualitative methods*

The qualitative physical land evaluation methods use expert knowledge derived from experiences of farmers and soil surveyors. This relatively simple procedure provides general results on the potentials and constraints of land for a defined land use. Characteristic results are expressions such as: 'high or low inputs are required', or 'land is moderately suited or unsuited'. No quantitative expressions of either inputs or outputs are given.

In Chapter 3 an example with use of expert knowledge was elaborated to evaluate the possibilities of applying slurry from animal manure in the Netherlands. A similar approach was followed in Chapter 5 to assess the growing potentials for sugar-beet in the European Communities (EC). Fast results can only be obtained, however, when the expert knowledge is captured in a computer system and linked to a geographical information system (GIS), as was discussed in Chapters 3 and 5 (Fig. 1). This implies that land evaluators can concentrate on their core responsibility. This involves defining the reasoning process to arrive at decisions on severity levels of land qualities and eventually on the overall suitability. Decision trees are used to capture the reasoning process. Such a complete decision tree is provided in Figure 2 (cf. Fig. 3, Chapter 3). This tree shows how the severity level for the land quality 'physical quality of the topsoil' was assessed for the evaluation of suitability for slurry injection. It was inferred from various land characteristics, such as parent material, soil texture, and groundwater depth class. Use of expert knowledge, captured in a computer system, implies that the evaluation of all land units is carried out quickly. It replaces the time-consuming application of the expert knowledge again and again to each unit by hand. The use of computers also assures that expert knowledge

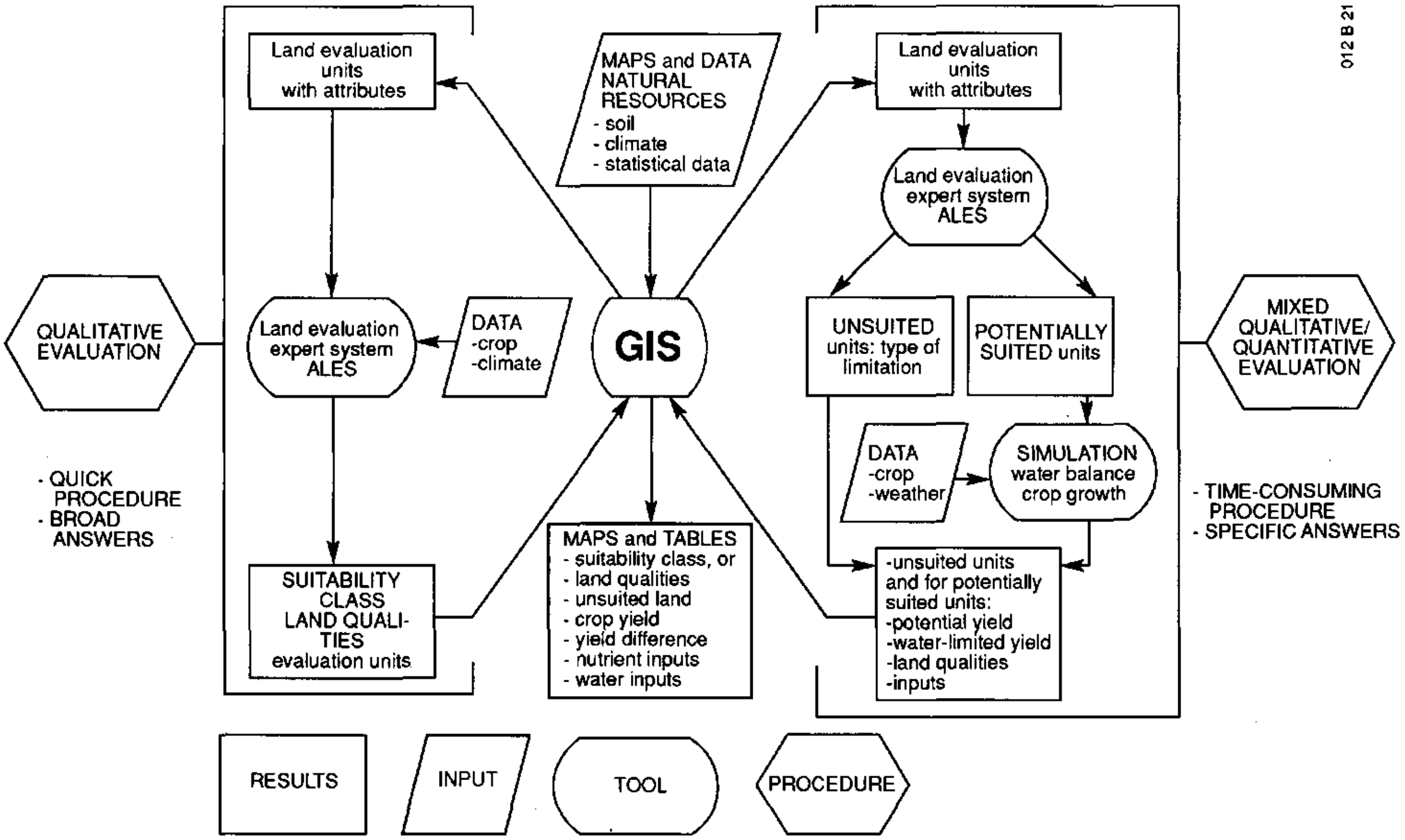


Fig. 1 Schematic outline of different physical land evaluation methods.

is made explicit and that the results are reproducible. In the Netherlands, computer-captured expert knowledge is being used to explore possibilities of Dutch land for application of various techniques to reduce NH_3 volatilization from animal manure (Wopereis, in press). Furthermore, possibilities of growing fibre crops are being investigated (Van Soesbergen et al., in prep.).

Applying qualitative methods to large areas of land with different agro-climatic regions implies that the crop yield potential within one suitability class can vary significantly in an absolute sense from region to region (Chapter 5). Differences in radiation and temperature between the regions cause substantial variation in crop yield potential for a certain suitability class, which is hard to incorporate in qualitative methods.

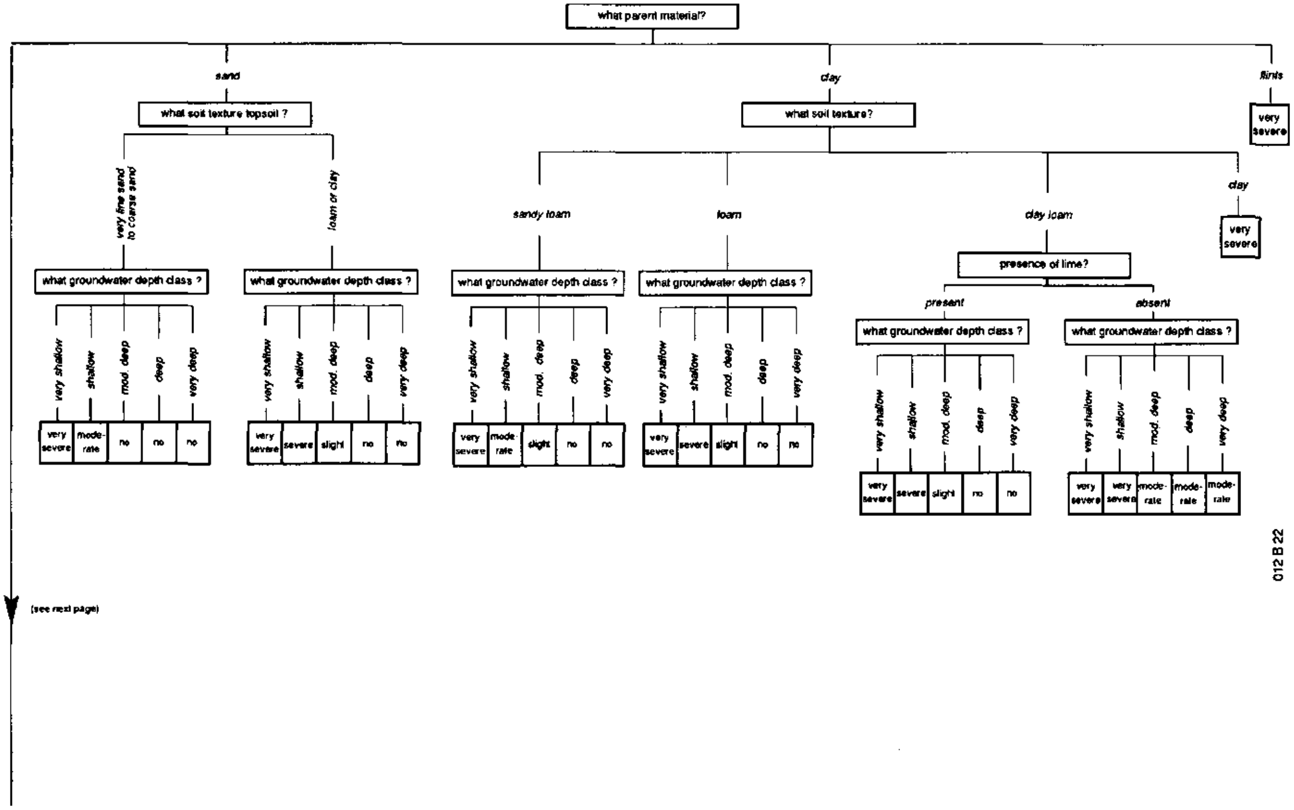
11.1.2 *Quantitative methods*

Quantitative physical land evaluation methods use dynamic, process-oriented computer models, simulating for instance soil-water flow and crop growth. The more complicated technical procedures provide quantitative expressions of the land qualities, and the suitability in terms of crop yields. Furthermore, the inputs to attain these yields are broadly quantified giving nutrients required to reach higher production levels or water demands for irrigation.

Within a quantitative land evaluation there can be various degrees of complexity for the models. In Chapters 4 to 10 inclusive both simple and sophisticated simulation models were used. Quantitative physical land evaluation has benefited substantially from the development of simulation models in other fields, e.g. hydrology and crop science (Section 2.2.3). The more complex models are based on descriptions of universally applicable physical and biological processes in the soil and crop. Mathematical expressions, which represent the transient processes, are incorporated in the simulation models. Crop- and site-specific models are obtained by specifying the appropriate parameters and boundary conditions. In Chapters 4, 6, 8, 9, and 10 water-associated land qualities, such as soil water deficits, soil aeration, and workability, were determined as the outcome of the quantitative evaluation. Estimated quantitative expressions for the crop yields of sugar-beet, potatoes, and wheat were presented in Chapters 5, 6, and 7.

In Chapter 6, a comprehensive relational diagram (Fig. 3, Chapter 6) was worked out showing the quantitative evaluation approach. In this context the term 'inferable land characteristic' was introduced. This type of characteristic is important in an operational sense. Inferable characteristics are either measured directly or deduced from readily available soil and land characteristics using pedotransfer functions. Examples of inferable characteristics are: bulk density, water retention data, and unsaturated hydraulic conductivity data. Inferable characteristics are essential input data for simulation models. Measuring all these inferable characteristics for every land unit is usually too expensive. Hence, the quantitative evaluation can benefit considerably from the development of pedotransfer functions (Section 2.2.3).

Many suitability criteria mentioned by Beek (1978) can be incorporated in the suitability assessment of the quantitative physical evaluation method, although process-oriented simulation models are still not able to deal with all suitability criteria adequately. This applies particularly to some criteria associated with farm management. In Chapter 5 it was shown that moderate limitations, such as a low cation exchange capacity or moderately steep slopes, are not yet properly included in the quantitative procedure. When these moderate limitations occur in the


what parent material?
sand
what soil texture topsoil ?
very fine sand to coarse sand
what groundwater depth class ?
very shallow
shallow
mod. deep
deep
very deep
very severe
mode- rate
no
no
no
loam or clay
what groundwater depth class ?
very shallow
shallow
mod. deep
deep
very deep
very severe
severe
slight
no
no
clay
what soil texture?
sandy loam
what groundwater depth class ?
very shallow
shallow
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very deep
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slight
no
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loam
what groundwater depth class ?
very shallow
shallow
mod. deep
deep
very deep
very severe
severe
slight
no
no
clay loam
presence of lime?
present
what groundwater depth class ?
very shallow
shallow
mod. deep
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very deep
very severe
severe
slight
no
no
absent
what groundwater depth class ?
very shallow
shallow
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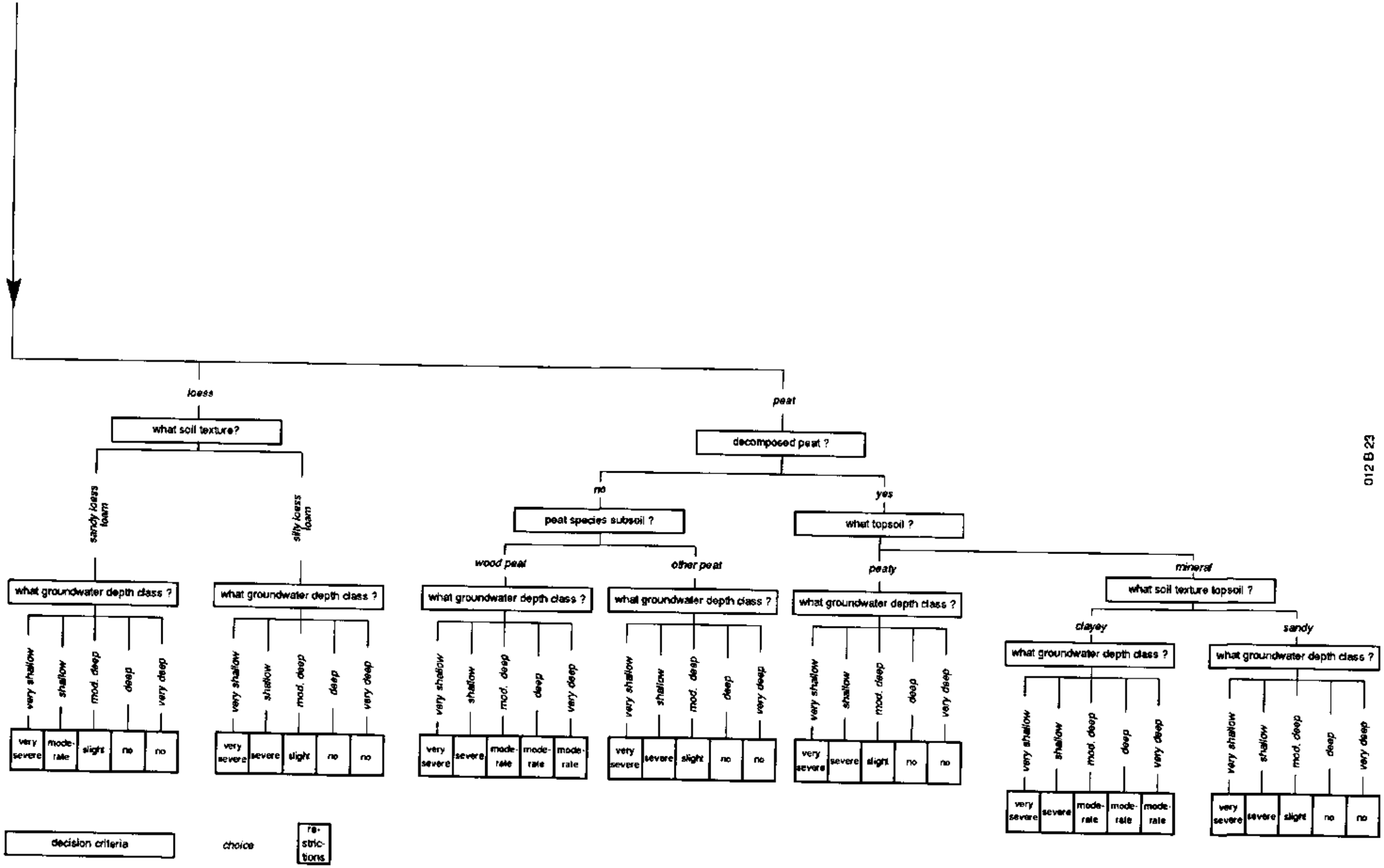

Fig. 2 The complete decision tree to determine the land quality 'physical quality of the topsoil' for assessing land suitability for slurry application from animal manure.

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region considered, they can usually be expressed in terms of costs for higher inputs defined within a land use type. Then, in the subsequent economic evaluation (see also Section 11.4) such land is likely to be evaluated as less suited for the defined use.

11.1.3 *Differences*

11.1.3.1 Assessing inputs

Qualitative and quantitative land evaluation methods differ in their capabilities to provide quantitative data on necessary inputs. For example, input of water and nutrients needed to reach a certain productivity has to be specified. Requirements of macronutrients, i.e. nitrogen, phosphorus and potassium, can be quantitatively determined with the quantitative methods. Requirements can then be calculated on the basis of the simulated dry-matter yield of stems, leaves, and storage organs of the crop, and of reported minimum and maximum concentrations of the nutrients in these crop parts. As an example, in this part of the thesis the requirements of macronutrients are computed for two medium-textured dystric Cambisols (Fig. 3). These soils occur in the regions of Bordeaux and Birmingham, and are identical to those for which the temporal variability of the sugar-beet yield was computed in Chapter 5. Under water-limited conditions the requirements of sugar-beet were found to be lower in the region of Bordeaux than in the region of Birmingham. The lower average yields in the former region cause these differences.

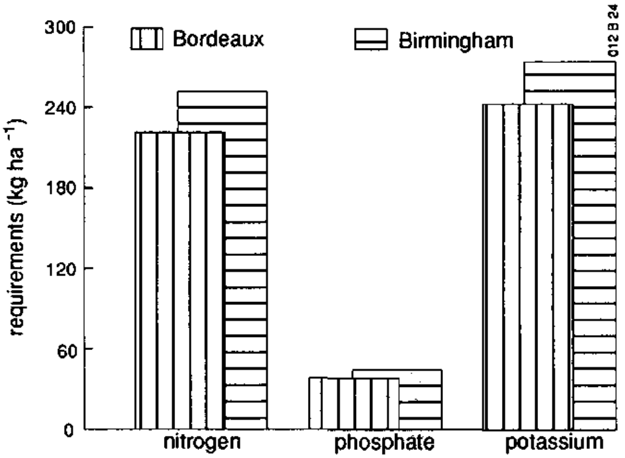

Fig. 3 Calculated average macronutrient requirements under water-limited conditions for sugar-beet grown on medium-textured dystric Cambisols in the regions of Birmingham (England) and Bordeaux (France).

Qualitative physical evaluation methods do not provide required inputs as an outcome of the evaluation. The inputs are derived from independent sources. They are specified for each of the suitability classes prior to comparing land units with the requirements of the land use types.

11.1.3.2 Type of limitation

In addition to the suitability class, qualitative methods specify the type of limitation as principal output (e.g. Fig. 3, Chapter 5). Such a specification can be useful when certain land improvements are considered. Quantitative methods provide crop yield as an integrated suitability criterion without information on the type of possible limitations. A comprehensive analysis of the model outcome has to be carried out to find which land characteristics are limiting. Sometimes a sensitivity analysis has to be performed.

11.1.3.3 Temporal variability

The outcome of a qualitative evaluation generally refers to long-term average weather conditions in a particular region. The temporal variability is not considered. Although the concept of qualitative methods does not impose restraints on taking into account inter-year variation, an extensive analysis can hardly be conducted. Such an analysis would become unmanageable. Conversely, simulation models in quantitative methods often consider relatively long weather records. This allows the probability distributions of land qualities and crop yields to be computed, as was illustrated in Chapters 4, 5, 6, 8, 9, and 10. These distributions are essential to risk analysis (e.g. Bouma, 1989a; Dumanski & Onofrei, 1989).

11.1.3.4 Potential conditions

Land evaluation primarily aims at exploring land use options (Chapter 1). Therefore, possibilities of analysing potential conditions are crucial. Qualitative physical land evaluation methods can sometimes handle potential situations. This is the case for potential conditions where one or more land qualities can be omitted. Present limitations of the land qualities are then assumed to be fully improved. Such an evaluation of potential conditions was demonstrated in Chapter 5, in which the land quality 'drought susceptibility' was simply omitted in assessing potentially suited land for irrigated agricultural use. Many land improvements, such as irrigation or drainage, cannot completely compensate for a soil limitation, and if they could the effects of a partial improvement should also be evaluated. This outcome is usually required for cost-benefit analyses. Qualitative methods can hardly assess the effects of partial improvements. Usually, the information obtained from a few typical situations is all there is available.

Quantitative evaluation methods are able to evaluate the effect of a full improvement of a land quality just like the qualitative ones. Moreover, they can satisfactorily examine the effects of a great number of partial improvements. For example, effects on crop yield of a large number of different groundwater depths to be realized by drainage (e.g. Werkgroep, 1987) or by groundwater extraction for drinking-water supply can be explored (e.g. Bouma et al., 1980; Van Lanen et al., 1987). The generally applicable physical and biological laws, on which the simulation models are founded, allow such analyses to be conducted.

Quantitative methods are also fit to explore potentials and constraints of land under conditions that may develop, but that exist nowhere yet. For instance, the crop growth potential can be assessed quantitatively for the situation that the carbon dioxide concentration is doubled due to a global climate change (e.g. Jansen, 1990; Van Diepen et al., 1990). Qualitative methods are not able to evaluate potentials and constraints of land for currently non-existing situations since they rely on extrapolation of knowledge from analogue situations only.

11.1.4 *Choosing the appropriate method*

The choice between a qualitative physical land evaluation method and a quantitative method is determined by the problem to be solved. Available resources, e.g. money and time, are also relevant. When quick and general answers are required, qualitative methods can be appropriate. When more detailed and specific results on the potentials and constraints of land for a defined land use are required, quantitative physical land evaluation methods become necessary. Applying quantitative methods, however, is more time-consuming because they need more data as input, and because more time is required for handling the input and output. Moreover, quantitative methods demand more computer time. Hence, qualitative and quantitative methods are **complementary** in terms of type of results and required efforts. Thus, there exists no 'best' physical land evaluation method for all problems to be encountered. The stage of planning or decision-making and the available resources determine which method is to be preferred.

Qualitative evaluation may also be applied in case of insufficient land data and restricted resources to gather additional data. Moreover, qualitative methods have been used successfully for evaluating minor crops, such as fruit trees or timber species (e.g. Hendriks et al., in press; Van Lanen et al., in press). For these evaluations insufficient crop data were available to use a quantitative method. In the latter case an attractive alternative would be to apply quantitative methods which take uncertainties in input data into account. Effects of these uncertainties are then also expressed in the final outcome. This approach is further discussed in Section 11.3.

11.1.5 *Mixed qualitative/quantitative evaluation*

Qualitative evaluation methods can cope with broad questions but, generally, in a later stage of planning or decision-making more specific and detailed results are required. When sufficient resources are available, quantitative methods can produce these results. As it is not sensible to apply the time-consuming quantitative methods to land units with obvious severe limitations, a mixed qualitative/quantitative physical evaluation approach was introduced (Fig. 1). For instance, poorly drained soils or steep slopes often prohibit many kinds of land use. The mixed approach involves applying qualitative methods to screen land for potential suitability. Land without severe limitations for a defined land use is determined (Step I). Subsequently, as step II, the quantitative methods are applied to potentially suited land (Fig. 1). The sequential application of qualitative and quantitative methods in the mixed approach is a way of **complementary** use of both methods. In Chapters 5 and 7, the mixed approach was applied to screen EC land for potentially suited land units for growing sugar-beet and wheat respectively. Only less than half of the EC area turned out to be potentially suited for these crops. This substantial reduction in the area to be evaluated shows the effectiveness of this selection before quantitative methods are applied (Fig. 9, Chapter 6). In Chapter 6, the mixed approach was further explained, and applied to define potentially suited land for potato-growing in the Netherlands.

11.2 USE OF THE LAND CHARACTERISTIC 'SOIL STRUCTURE' IN PHYSICAL LAND EVALUATION ON FARM SCALE

Chapters 8, 9 and 10, demonstrated the importance of the land characteristic 'soil-structure type' to the quantitative assessment of water-associated land qualities on farm scale. The land qualities soil-water deficit, soil aeration, and workability were calculated using quantitative physical land evaluation methods. Differences between land qualities of sandy loam and clay loam soils only differing in soil-structure type were interpreted as being due to soil-structure degradation. This degradation was associated with different soil management practices. Moreover, possible effects of soil-structure regeneration were explored.

On farm scale, soil surveyors have been able to reproducibly recognize different soil-structure types. They have observed different types developed in permanent grassland, in arable land with a ploughpan, or in arable land with a disrupted ploughpan. The soil-structure types recognized could be related to current Dutch soil management practices. The soil-structure types were characterized by different soil characteristics which were included in the quantitative physical land evaluation process (Fig. 2, Chapter 6). Thus, differences in land qualities between soil-structure types were calculated. The changes in number of workable days, days with an inadequate soil aeration, and soil-water deficits owing to management practices were quantitatively assessed. The difference between the land qualities of a less favourable soil-structure type and those of the most favourable one (the permanent grassland type) was interpreted as the maximum effect that may be attained by improving current soil management practices.

For the above-mentioned clay loam soils, the computer model simulating soil-water flow had to be adapted to quantify the effects of soil management on the land qualities (Chapter 9). The clay loam soils considered are characterized by the presence of macropores, i.e. cracks and worm channels. These macropores cause free water to bypass the unsaturated topsoil without wetting it, and bypass water to infiltrate directly into the subsoil. Use of a conventional soil-water flow model, which is based on the Darcy-Richards' theory, would have produced quite unrealistic results for the clay loam soils (e.g. Bouma, 1989a). Concepts of conventional models apply only to rigid, isotropic porous media (e.g. Klute, 1973). A few approaches have been developed to model flow processes in clay soils (e.g. Bouma & Booltink, 1990): (1) a fundamental approach which takes swelling and shrinkage into account by considering the change in coordinates for the flow system (e.g. Youngs, 1983; Smiles, 1984), and (2) an approach which simulates the transient volume and depth of cracks due to swelling and shrinkage, by incorporating shrinkage characteristics in a soil-water flow model (e.g. Bronswijk, 1988). A third approach introduced in this thesis (Chapters 9 and 10) is based on the application of an adapted soil-water flow model and uses soil-morphological features. A conventional soil-water flow model was modified allowing the amount of bypass water to be calculated as a function of rainfall depth and the pressure head of water in the topsoil. The relationship between the amount of bypass water and the pressure head was measured in the laboratory using undisturbed soil samples and a rainfall simulator. This relationship was used to broadly account for the dynamic nature of characteristics governing bypass flow. Furthermore, the model was adapted to incorporate the infiltration of bypass water in dead-end pores at certain depths in the subsoil. This subsurface infiltration was called 'internal catchment'. The different depths of infiltration were estimated from vertical continuity of macropores using morphological techniques in the field and the laboratory. Different bypass relationships and vertical continuities of macropores were measured for the two soil-structure types of the clay loam soils (Chapter 10; Van Lanen & Boersma, 1988). Lateral infiltration into the walls of the macropores was not considered. Of course this is a simplification of reality. The study presented in Chapters 9 and 10 demonstrates the importance of considering bypass flow and internal catchment for field conditions in soils with a cracking topsoil and a non-cracking, more sandy subsoil. These conditions are common in many alluvial soils in which fining upwards has been the dominant sedimentation process. Bypass flow can have major consequences for certain land uses. It may increase the number of machinery-work days, but soil-water deficits may increase as well. Moreover, solutes are transported beyond the root zone more easily than in rigid soils (e.g. Bouma & Booltink, 1990).

11.3 SHORTCOMINGS OF PHYSICAL LAND EVALUATION

As mentioned in Chapter 1, the physical land evaluation methods in this thesis should be considered as a contribution to a further development of land evaluation methods. Therefore, some elements are not yet included. The following section mentions some of these elements, and discusses possible solutions.

11.3.1 *Reliability of the results*

The reliability of the results obtained with physical land evaluation methods depends, amongst other things, on the representation of the relevant processes in the model. In the case of an expert model, the reliability depends on the representation of relevant experts' judgement. Furthermore, the reliability is determined by the not site-specific model parameters and the site-specific data on soil system and climate.

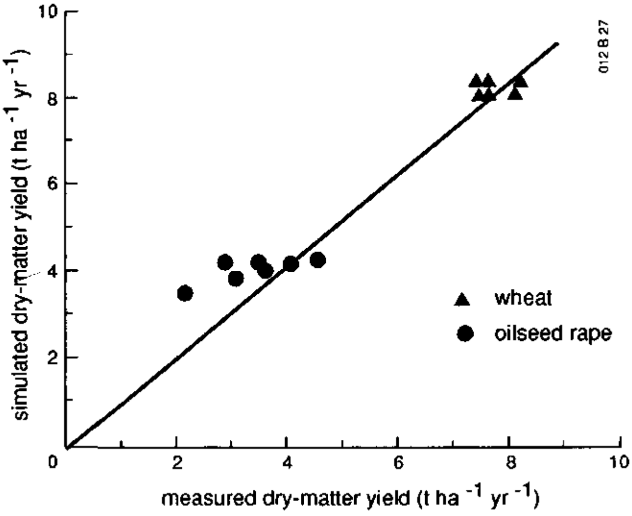

Fig. 4 Comparing observed and simulated potential crop yields using WOFOST.

It is generally thought that a model should be calibrated and validated to check its acceptability (e.g. Feyen, 1987). The results in Chapters 6, 8, and 10 were obtained from calibrated and sometimes validated methods (cf. Fig. 2, Chapter 8; Fig. 3, Chapter 10; Hack-ten Broeke et al., 1990). The simulation model applied in Chapters 5 and 7 was slightly recalibrated using observed and predicted yields of some crops (Fig. 4). The other results were not from comprehensively calibrated methods. The simulation models used in Chapters 4 to 10 inclusive were extensively validated during their development. Their performance has been investigated for a wide range of locations with different soils and climates. Hence, the models with not site-specific parameters were accepted to apply to conditions defined by other soil and climate data.

Land evaluators do not focus on calibrating and validating simulation models for current land performance. Their investigations are directed to evaluating land for potential situations, and the models are predominantly applied to cope with questions such as 'what will happen if land use will change so-and-so'. Furthermore, an acceptable agreement between observed and predicted current performance of land is not a guarantee for an identical agreement in the potential situation (e.g. Van Lanen, 1981). Actually, if the models ought to be comprehensively calibrated and validated, this should focus on the potential situation itself. Such a validation should involve experiments to be conducted on many land units. All intended land uses should be considered during a period long enough to encounter all the relevant weather conditions. Validation on this scale is obviously impossible. Moreover, if all these data on projected land uses were available, there would be no need for a land evaluation model. Furthermore, particular potential conditions can hardly be realized under field conditions. For instance, land performance under doubled carbon dioxide concentrations can only be investigated in closed chambers. The irrelevance of extensive calibration and validation of simulation models to land evaluation also applies to expert models according to Rossiter (1990). Therefore, land evaluators have to rely on the best current knowledge of processes and parameters.

Reliability of the results obtained with land evaluation methods also depends on the quality of the site-specific soil and climate data. In Chapters 3 to 7 inclusive a conventional procedure was applied (see also Bouma, 1989a; 1989b), based on soil and climate maps consisting of delineated mapping units. In these studies, attention was predominantly focused on variability between mapping units, and not within the mapping units. General-purpose maps were used in the above-mentioned chapters instead of data of individual points as proposed by De Wit & Van Keulen (1987). A main reason for this procedure was the availability of maps and the inaccessibility of data of individual points. Moreover, the maps were supposed to provide a basis for interpreting land resource data, which is as good as maps derived from point data that were aggregated in a statistical way (e.g. Bregt et al., 1987). In the studies on farm scale (Chapters 8, 9, and 10), part of the spatial variability within a mapping unit was accounted for by considering soil-structure types. Recognizing soil-structure types and using them as more homogeneous units (strata) to analyse spatial variability increases the number of units, but it may reduce the variability of these units. Spatial variability within units defined by soil-structure was not dealt with in this thesis.

In the conventional procedure, each of the mapping units is characterized by either a representative soil profile or a representative meteorological station. This approach implies a subdivision of land with sharp boundaries (e.g. Fig. 3, Chapter 7). This approach has to be considered as a first approximation, because natural boundaries generally tend to be more gradual. Techniques such as 'fuzzy clustering', considering gradually changing boundaries (e.g.

Burrough, 1986), are currently available. Basic data are yet lacking to apply these techniques in investigations like ours.

Selection of a representative soil profile or meteorological station is based on expert judgement. For instance, the description of a representative soil profile (RPD) is based on a pedological clustering by a soil surveyor using the observed data of individual borings. Because of spatial variability within a unit and lack of strict procedures to cope with this, an RPD is rather subjective and shows differences between individual surveyors (De Gruijter & Marsman, 1985). The usefulness of RPDs also depends on the map scale. Wösten et al. (1987) and Bregt & Beemster (1989) show that use of RPDs belonging to maps on scales from 1 : 10 000 to 1 : 50 000 produces rather unrealistic values for land qualities or crop yield for individual parcels or points. For relatively large areas of land, however, they illustrate that average values of land qualities or crop yield can be reasonably well predicted using the RPDs of the map with the smallest scale.

Instead of using representative soil profiles for a mapping unit, it would be attractive to use probability distribution functions of the land characteristics. Both expert models and simulation models can handle these distribution functions as input. The methods are able to convert these functions into results expressed as probabilities of occurrence. This approach is an attractive alternative to the conventional ones. Distribution functions of input variables can refer to both site-specific data and to not site-specific model parameters. The distribution function of input variables with generally a normal or log-normal appearance can be obtained from conventional statistical procedures (e.g. Kros et al., 1990; Finke et al., in press). An alternative to these statistical procedures is scaling. Scaling is usually applied to simplify the description of spatial variability of soil hydraulic characteristics (e.g. Ahuja et al., 1984, Hopmans, 1987; Wösten, 1990).

A well-known method to convert occurrence probabilities of input into output of simulation models is the Monte-Carlo procedure. The Monte-Carlo procedure starts by establishing simultaneous probability distributions. Then, a series of samples is taken from these distributions as model input considering the correlation between the model input variables as well. The simulation model is run for each set of sampled input, yielding one realization of output variables. Finally, after repeatedly running the model, the probability distribution of each output variable can be computed. The distribution function is usually expressed in terms of the mean and standard deviation. An analysis of soil-water flow by an univariate elaboration of the Monte-Carlo procedure is given by Jensen & Butts (1986). A multivariate approach for investigating the uncertainties in predicted soil acidification is presented by Kros et al. (1990). Both examples refer to a point or field-scale analysis. A regional application is given by Petach & Wagenet (1989) and Petach et al. (in press), who applied a comprehensive multivariate Monte-Carlo procedure linked to a GIS. They have produced occurrence probabilities of water fluxes and pesticide fluxes for an area of 70 km^2. In their analysis they also included temporal variability due to inter-year weather differences. The above-mentioned studies used conventional statistical procedures to generate distribution functions for input variables. Hopmans & Stricker (1989) demonstrate how scaled functions of hydraulic characteristics can be combined with a Monte-Carlo procedure. Their application refers to a stochastic analysis of the soil-water regime in a small Dutch experimental catchment.

Although technical procedures are available to cope with spatial variability within a mapping unit and its effect on model output, they were not applied in the chapters of part II. There were insufficient basic data to compute the distribution functions for the input variables. A partial sensitivity analysis was applied to show at least that the results produced do not represent the absolute truth (Chapter 7). Examples of such an analysis for the investigations on soil-structure types were given (Chapter 8; Fig. 7, Chapter 9). The relative yield (Fig. 5) simulated with the model used in Chapters 5 and 7 illustrates the importance of a reasonable estimate of the soil depth in case of relatively shallow soil depths. Figure 5 also shows that the results presented for the European Communities might deviate several per cents from 'reality' for some land units with shallow soil depths.

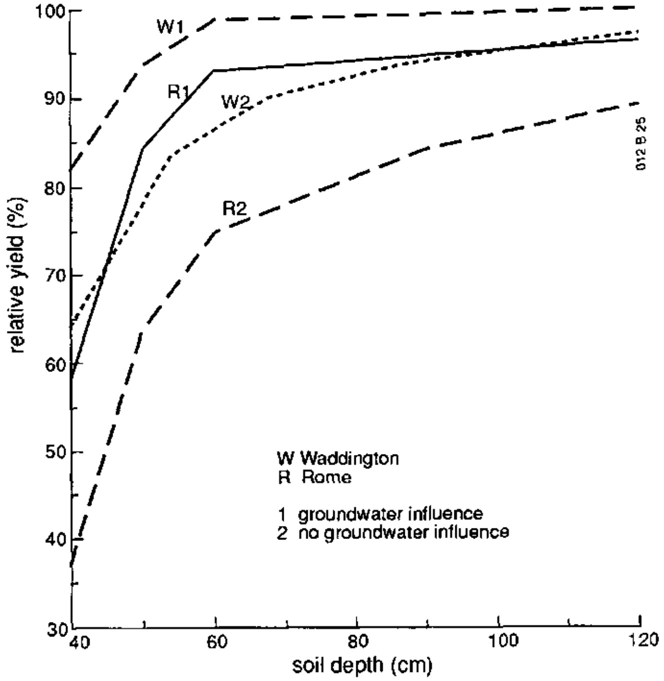

Fig. 5 Effect of soil depth of coarse-textured soils on simulated average water-limited wheat grain yield (as dry matter) in some agro-climatological regions (100% = 9 t ha^{-1} yr^{-1}).

Nowadays, users of land evaluation data still accept that the reliability cannot be quantified adequately. As land evaluation is primarily directed to comparing alternatives, they accept methods producing a reasonable estimate of the absolute level of land qualities and crop yields. It is to be expected, however, that quantitative expressions for the reliability have to be provided in future. Therefore, much work is to be done to collect the basic data to characterize the spatial variability of mapping units. This especially applies to small-scale maps, as used in our studies.

11.3.2 *Environmental aspects*

Besides land productivity, the vulnerability of land is recognized as an important topic nowadays. The impact of agricultural production on the environment must be known for many purposes (e.g. Bouma et al., 1986; Breeuwsma et al., 1986). In some cases, qualitative physical land evaluation can provide broad answers aiming at environmental protection purposes. This was demonstrated by evaluating the possibilities of slurry injection in Chapter 3. Some other examples with similar technical procedures are: assessing the nitrogen loss potential (Malzer et al., 1983), and evaluating groundwater vulnerability to nitrate pollution (Palmer, 1987). In these approaches, data on soil, climate and management are combined and they yield results such as 'low' or 'high' loss potential or vulnerability. As a first approximation these expressions are useful. Eventually, more specific results will be needed, because targets in environmental legislation are generally formulated in quantitative terms. In this thesis, no quantitative physical land evaluation methods were developed for such demands. Required input of macronutrients as computed in broad terms (Fig. 3) was assessed, but impact on environment due to losses was not.

Comprehensive knowledge of dynamics of soil-water flow, chemical processes, and crop growth is required to explore agricultural production strategies that are ecologically sound and still profitable. A number of concepts and many models were developed during the eighties to simulate one or more aspects of solute flow (e.g. Addiscott & Wagenet, 1985; Vachaud et al., 1990). For land evaluation purposes, integrated simulation models should be developed accounting for the dynamics of the above-mentioned processes and their interactions. These models should allow water flow and crop growth to be predicted, as well as solute transport, transformation, nutrient uptake, and other losses from the soil. Effects of various management practices and measures on these processes need to be simulated as well. The model concepts must apply to a wide range of soil types and climates. Currently functional, less-mechanistic (Addiscot & Wagenet, 1985) models already provide relevant quantitative data for some environmental land qualities. For instance, Breeuwsma et al. (1986) present a map showing the distribution of the phosphate sorption capacity in a Dutch region with an area of 2000 ha. To simulate the behaviour of nitrogen and its compounds in the soil many models are available. These models vary from functional to more or less mechanistic (e.g. Vachaud et al., 1990). Recently, a number of these models were compared and reviewed within an EC project on 'Nitrate in Soils'. It appeared that mineralization, denitrification, and nitrogen uptake processes are not yet well understood. However, nitrate leaching from the root zone, being the objective of the research project, was adequately simulated (Reiniger et al., 1990; Vereecken, in press).

As already stated, further development of models towards more integrated models for land evaluation is necessary. Such a development, however, is only meaningful when basic data are collected as well.

11.4 PHYSICAL AND INTEGRAL LAND EVALUATIONS

The significance of physical land evaluation is greatly determined by its subsequent use in integral land evaluation as a means of exploring land use options (Chapter 1). Physical land evaluation can substantially contribute to various kinds of land use planning on different scales. For instance, physical land evaluation can help a farmer to decide on implementing a drainage system or on adapting his cropping system. It can also assist the national government to formulate a general policy on land use. Physical land evaluation plays a vital part in exploring land use options, but by itself it does not provide sufficient information for land use policies and guidelines. For this purpose, physical land evaluation should be part of an integral land evaluation procedure. Integral land evaluation synthesizes information on the nature and productivity of the land resources with information on demands and constraints for land use (Beek, 1978; Vink, 1982; Smit et al., 1984). The latter has a clear socio-economic setting. Actually, integral land evaluation is an extension of physical evaluation in so far as it identifies land use options in socio-economic terms (Dumanski & Onofrei, 1989).

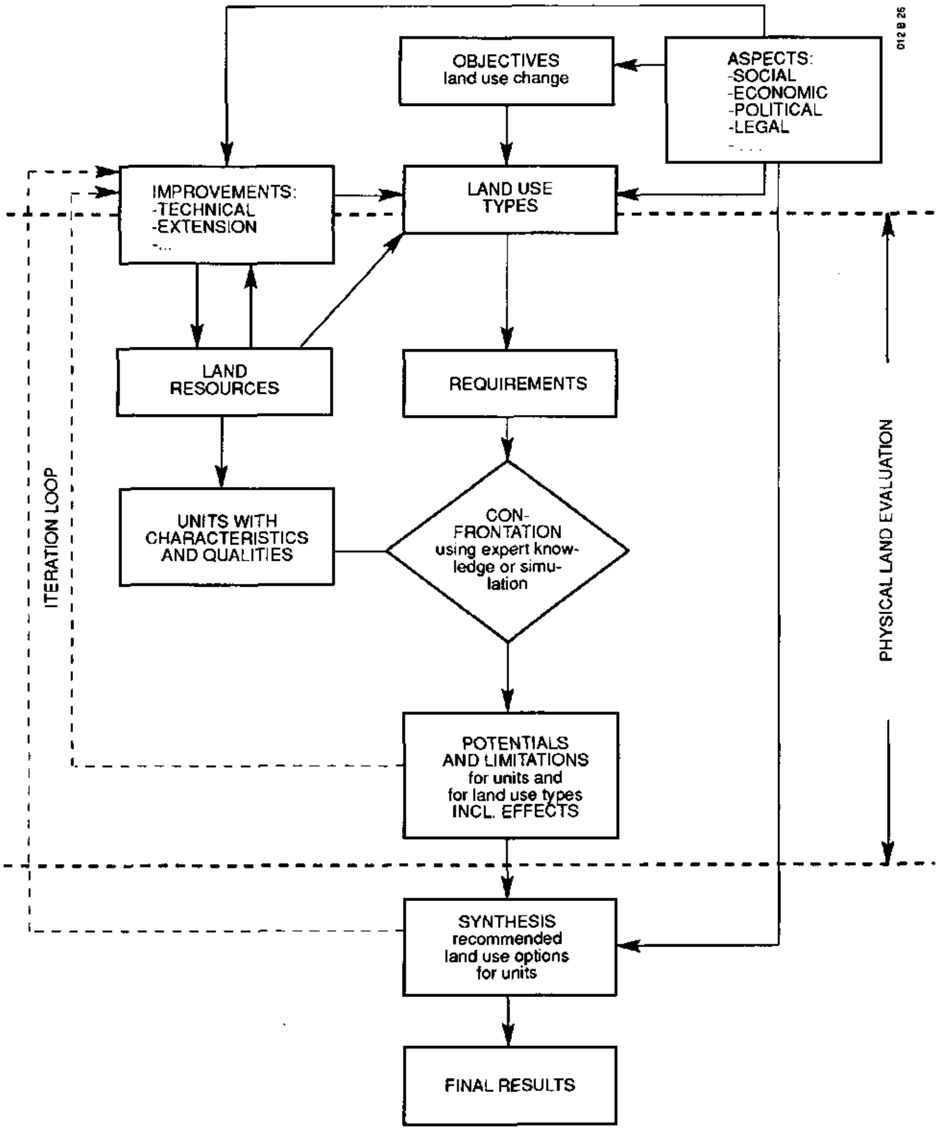

Fig.6 Schematic outline of the integral land evaluation procedure and the place of physical land evaluation.

As explained above, physical land evaluation involves that land qualities and overall suitability are assessed for a certain land use type (Fig. 6). According to FAO standards (Food, 1976) the selected land use types (LUTs) must be 'physically and socio-economically relevant to the considered region' (cf. Chapter 2). This means that selecting and describing LUTs is partly beyond the scope of physical land evaluation (Fig. 6). Physical land evaluation is usually conducted by a team of soil surveyors and agronomists. When detailed LUTs are intended to be formulated, cooperation with economists and input from social sciences is a prerequisite to adequately deal with all kinds of non-land aspects. In practice, this requirement is not often met sufficiently, or it should be investigated more thoroughly. Scientists who are familiar with farming system analysis can probably contribute to the analysis of bio-physical potentials and farmers' socio-economic production constraints, relevant to the selection and description of the LUTs (e.g. Fresco et al., 1990).

Physical land evaluation starts with the LUTs described in terms of inputs and requirements. Moreover, the potentials and limitations of each land unit for these LUTs are given. An assessment of the impact on environment must be provided as well (Fig. 6). When the outcome of the physical evaluation is sufficient in terms of exploring land use options, no subsequent analysis is performed. For instance, in the case of slurry injection (Chapter 3), no subsequent analysis was necessary to decide on possibilities for slurry injection in Dutch grassland regions. In other cases a synthesis study can be performed. Then the bio-physical potentials and constraints are confronted with social, economic, and political aspects. These aspects usually have some conflicting elements.

Smit et al. (1984) present a mathematical model for the synthesis phase of an integral land evaluation procedure. The model provides quantitative data on land use flexibility and the critical importance of particular regions for specified land uses in the province of Ontario (Canada). The model uses data on the potential of regional crop production, socio-economic conditions and production targets as input. The model does not predict optimal land use patterns, but it rather specifies whether the range of land use options in the considered regions is narrow or wide. It also specifies which regions and uses mostly limit the range of options. Furthermore, it provides sensitivity data, which is a prediction of the impact of changes in policies or conditions on the range of land use options.

Another well-known quantitative approach for the synthesis phase of integral land evaluation is interactive multiple goal linear programming (IMGP). This method can be applied to search for feasible land use scenarios (e.g. Van Keulen & Van de Ven, 1988). Objectives, such as maximizing yield per unit area, maximizing employment in agriculture, minimizing production costs, and minimizing nutrient leaching either per unit product or per unit area, can be optimized at the same time. Depending on the selection of the objectives and the weights allocated to the objectives, scenarios for land use are generated. The scenarios reflect different socio-economic options. The results of the study of regional crop growth potential of the European Communities (Chapters 5 and 7) are also being used as input for an IMGP application by the Dutch Scientific Council for Government Policy. Applying IMGP with these data as one of the inputs allows feasible land scenarios for the rural areas within the European Communities to be investigated (Van Latesteijn, 1990).

The final product of the synthesis phase should be a number of land use options (Fig. 6), which can be used by the government, regional administrative bodies, and land owners for their decisions.

An interesting development for the use of results of the different physical land evaluation methods for land use planning is the comprehensive LEFSA (Land Evaluation Farming System Analysis) sequence. This LEFSA sequence is worked out by the International Institute for Aerospace Survey and Earth Sciences (ITC), Wageningen Agricultural University, and the Centre for Agrobiological Research (CABO) in cooperation with FAO (Fresco et al. (1990). In this joint Dutch-FAO effort an approach is elaborated showing how physical land evaluation can be integrated into an agricultural land use planning process, using farming system analysis as well. The LEFSA sequence resembles an integral land evaluation procedure, combining the strong points of land evaluation and farming system analysis. LEFSA shows how the land use planning process can be executed within an agricultural hierarchy. To establish a regional land use plan, the process starts at the national level or even higher (e.g. European Communities), and then proceeds downwards to the regional, subregional, farm, and finally subsystem levels (e.g. crop or herd subsystem). At each level, a particular type of physical land evaluation is proposed. At the national or supra-national level broad assessments are required, whereas at the (sub)regional, farm, and subsystem levels an increasing degree of detail is needed. The elaborated qualitative and quantitative physical land evaluation methods in this thesis are expected to fit well into the level approach of the LEFSA procedure.

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SAMENVATTING

KWALITATIEVE EN KWANTITATIEVE FYSIEKE LANDEVALUATIE: EEN OPERATIONELE AANPAK

In grote delen van de wereld zal het agrarisch landgebruik moeten worden aangepast. In de ontwikkelingslanden zal de produktie per eenheid van oppervlakte moeten worden vergroot, terwijl in de ontwikkelde landen de overproduktie van sommige voedselgewassen zal moeten worden teruggedrongen. Verder zullen duurzame, agrarische produktiesytemen moeten worden ontwikkeld die ook het behoud, en zonodig het herstel, van het milieu, de natuur en het landschap ten doel hebben. Er zullen dus vragen moeten worden beantwoord, zoals: "Welke mogelijkheden zijn er voor nieuwe gewassen, welk effect heeft een verandering van de kunstmestgift, of hoe groot is de oppervlakte waarop milieuvriendelijke technieken kunnen worden ingezet?" Verder moet ook kunnen worden geschat in welke mate de produktie van overschotgewassen nog zou kunnen groeien, indien geen produktiebeperkende maatregelen worden genomen. Beslissingen over nieuwe vormen van landgebruik kunnen echter pas verantwoord worden genomen, nadat de sociaal-economische omstandigheden en de mogelijkheden en beperkingen van het fysieke milieu diepgaand zijn geanalyseerd. Eerstgenoemde omstandigheden zijn sterk tijdafhankelijk, terwijl het fysieke milieu, zoals de bodem, het klimaat, de topografie en de hydrologie, veel stabieler is. Deze verschillen houden in, dat de resultaten van de evaluatie van het fysieke milieu voor een bepaalde landgebruiksvorm veel langer geldig zijn dan de resultaten van een integrale evaluatie, waarin ook de sociaal-econmische aspecten zijn verdisconteerd. Vanwege de verschillen in tijdsgeldigheid heeft zich het vakgebied van de fysieke landevaluatie ontwikkeld. De fysieke landevaluatie houdt zich, als onderdeel van de integrale landevaluatie, bezig met de evaluatie van de mogelijkheden en beperkingen van het fysieke milieu voor een mogelijke relevante vorm van landgebruik.

Binnen de fysieke landevaluatie zijn er verschillende technische procedures ontwikkeld om het land te evalueren. Deze procedures variëren van relatief simpele methoden die uitgaan van deskundige kennis, tot complexere methoden die gebruik maken van simulatiemodellen. De deskundige kennis wordt vaak ontleend aan de ervaringen van boeren en veldbodemkundigen. Zij baseren hun kennis op een jarenlange observatie van de reactie van gewassen op verschillende gronden, waarbij ook de invloed van het weer en bedrijfsmaatregelen worden betrokken. De resultaten van procedures gebaseerd op deskundige kennis zijn beschrijvend van aard. De methoden worden daarom aangeduid als kwalitatieve fysieke landevaluatiemethoden. Karakteristieke antwoorden van de kwalitative methoden zijn bijvoorbeeld: "een landeenheid met ruime mogelijkheden" of "een slechte bewerkbaarheid". De gewasopbrengst of het aantal werkbare dagen worden niet gekwantificeerd. De complexere procedures daarentegen die gebruik maken van computermodellen, produceren wel dit type antwoorden. De modellen simuleren de waterstroming in de bodem, en de verdamping en groei van gewassen onder een groot aantal verschillende omstandigheden. Deze modellen worden als proces-georiënteerde modellen aangeduid. Met deze modellen kan bijvoorbeeld het gemiddelde bodemvochttekort worden gesimuleerd. Ook wordt met behulp van historische weerreeksen de kans berekend dat een bepaald tekort wordt overschreden. Verder kan de kansverdeling van het aantal werkbare dagen worden vastgesteld en kan de gemiddelde produktie voor een aantal gewassen alsmede de kansverdeling daarvan worden bepaald. Vanwege het specifiekere karakter van de resultaten die verkregen worden met de computermodellen, worden deze procedures aangeduid als kwantitatieve fysieke landevaluatiemethoden.

In Hoofdstuk 2 van dit proefschrift wordt achtergrondinformatie gegeven over de ontwikkeling van de fysieke landevaluatiemethoden. Allereerst worden de internationale ontwikkelingen beschreven. Hierbij is onderscheid gemaakt tussen kwalitatieve methoden die gebaseerd zijn op deskundige kennis, zoals het systeem dat ontwikkeld is door de Wereldvoedsel-Organisatie van de Verenigde Naties, en kwalitatieve methoden die gebruik maken van formules (parametrische methoden). Een bekend voorbeeld van de laatstgenoemde groep is het Duitse Bodenschätzung-systeem. Naast de kwalitatieve methoden wordt ook de opkomst van de kwantitative methoden beschreven, die mogelijk werd gemaakt werd door ontwikkelingen in de computertechnologie. Hierdoor konden proces-georiënteerde simulatiemodellen worden gebruikt voor landevaluatiedoeleinden. In het tweede gedeelte van Hoofdstuk 2 worden de landevaluatiemethoden beschreven zoals die na 1945 zijn ontwikkeld voor toepassing in Nederland. Aan de hand van ontwikkelingen gedurende vier perioden wordt de toenemende kwantificering van de landevaluatie geschetst.

Het tweede gedeelte van dit proefschrift bestaat uit acht hoofdstukken (Hoofdstukken 3 tot en met 10) die de ontwikkelde kwalitatieve en kwantitatieve evaluatiemethoden beschrijven. Verder worden toepassingen beschreven voor Nederland en de Europese Gemeenschappen (EG) aan de hand waarvan de mogelijkheden van de methoden worden geïllustreerd en waarmee enkele alternatieve vormen van landgebruik worden verkend. Ook worden de resultaten van beide methoden vergeleken.

In Hoofdstuk 3 wordt met behulp van kwalitative landevaluatie aangegeven welke mogelijkheden er in Nederland bestaan voor de injectie van drijfmest. Een kennismodel is ontwikkeld dat in een computersysteem is opgeslagen. Algemene antwoorden, in de vorm van oppervlakten van Nederland die veel of weinig mogelijkheden hebben voor mestinjectie, konden zeer snel worden verkregen door ontwikkeling van deze kennismodellen en de koppeling daarvan met een geografisch informatiesysteem (GIS). Uit het onderzoek, waarbij gebruik werd gemaakt van de Bodemkaart van Nederland 1 : 250 000, bleek dat een aanzienlijk deel van de Nederlandse graslandgronden weinig of geen mogelijkheden heeft voor mestinjectie.

In de Hoofdstukken 4 en 5 worden kwalitatieve en kwantitatieve evaluatiemethoden onderling vergeleken. In Hoofstuk 4 gebeurt dit voor landhoedanigheden, zoals het bodemvochttekort en de bodemaëratie. De statische resultaten van enkele bestaande kwalitatieve methoden worden voor vier kaarteenheden gepresenteerd en vergeleken met de kansverdelingen verkregen met simulatiemodellen. In Hoofdstuk 5 wordt het geschatte produktiepotentieel voor suikerbieten in de EG gebruikt als vergelijkingsobject. De gewasgroeimogelijkheden voor vele duizenden kaarteenheden zijn daartoe bepaald. Voor de kwalitatieve methode is een kennismodel ontwikkeld dat gekoppeld aan een GIS relatief snel de geschiktheidsklasse en zonodig het type beperking geeft. In de kwantitatieve aanpak is een computermodel dat de waterbalans van de bodem, de gewasverdamping en de gewasgroei simuleert, gekoppeld aan hetzelfde GIS. De langjarig gemiddelde opbrengst alsmede de kansverdeling ten gevolge van weersverschillen zijn hiermee bepaald. Minder dan eenderde deel van de EG blijkt onder regen-afhankelijke omstandigheden geschikt te zijn voor de verbouw van suikerbieten. Voor dit deel van de EG worden de geschiktheidsklassen van de kwalitatieve methoden vergeleken met de gesimuleerde opbrengsten van de kwantitatieve methoden. De geschiktheidsklassen binnen een geografische eenheid blijken goed te kunnen worden gekarakteriseerd met de gesimuleerde opbrengsten, indien de agro-klimatologische verschillen binnen de eenheid niet te groot zijn.

In Hoofdstuk 6 wordt de kwantitative fysieke landevaluatiemethode uitgewerkt en geïllustreerd met de mogelijkheden voor aardappelteelt in Nederland. Een relationeel diagram toont de relatie tussen landkenmerken, landhoedanigheden en de geschiktheid in termen van gewasgroei. De plaats van simulatiemodellen voor stroming van water in de bodem, gewasverdamping en gewasgroei wordt aangegeven. In dit kader wordt ook het begrip "afleidbaar landkenmerk" geïntroduceerd. Dit type landkenmerken kan zowel worden gemeten, hetgeen vaak tijdrovend en kostbaar is, of worden afgeleid uit gemakkelijk beschikbare landkenmerken met behulp van vertaalfuncties. Omdat de afleidbare kenmerken belangrijke invoergegevens zijn voor de simulatiemodellen, zijn ze in operationele zin, samen met de vertaalfuncties, van groot belang. Kwantitatieve evaluatiemethoden leveren specifiekere resultaten op dan kwalitatieve methoden, maar de toepassing ervan vraagt meer tijd en ook specifiekere invoergegevens. Daarom wordt een gemengde kwalitatieve/kwantitatieve evaluatiemethode geïntroduceerd. Landeenheden met duidelijke beperkingen voor een bepaalde gebruiksvorm worden in een eerste fase opgespoord. Dit gebeurt relatief snel met kwalitatieve methoden, waarvan de kennismodellen in een computersysteem zijn opgeslagen. De kwantitatieve methoden worden in de daaropvolgende fase toegepast op potentieel geschikt land. Ongeveer 65% van Nederland blijkt potentieel geschikt te zijn voor de verbouw van aardappelen. Dit percentage is overigens afhankelijk van de schaal van de bodemkaart die gebruikt wordt voor het opsporen van kaarteenheden met duidelijke beperkingen. Naarmate de kaartschaal kleiner wordt, zal het percentage potentieel geschikt land toenemen. Relatief simpele en complexere simulatiemodellen zijn vervolgens toegepast op kleine oppervlakten van het potentieel geschikte gebied om de mogelijkheden van kwantitative methoden te demonstreren. Hierbij worden gedetailleerdere bodemkaarten gebruikt. Deze gedetailleerde analyse toont aan dat in een bepaald zandgebied slechts op een klein gedeelte van het potentieel geschikte gebied ook daadwerkelijk hoge opbrensten kunnen worden gehaald. Aan het einde van het hoofdstuk wordt een schatting gemaakt van de tijd die kan worden bespaard door de gemengde evaluatiemethode toe te passen in plaats van uitsluitend de kwantitatieve methode. Hetzelfde is ook gedaan voor de toepassing van simpele modellen in de kwantitatieve aanpak in plaats van complexere modellen.

In Hoofdstuk 7 is de gemengde kwalitatieve/kwantitatieve evaluatiemethode verder uitgewerkt om de groeimogelijkheden van tarwe in de EG te verkennen. In dit hoofdstuk wordt de belangrijke koppeling in operationeel opzicht van landevaluatiemethoden met een GIS beschreven. Het gebruik van gedigitaliseerde kaarten, zoals de Bodemkaart van de Europese Gemeenschappen 1 : 1 000 000 en een kaart met agro-klimatologische regio's, was noodzakelijk. Voor de eerste fase van de evaluatie is een kennismodel ontwikkeld waarmee land met duidelijke beperkingen is opgespoord. Minder dan de helft van de EG blijkt potentieel geschikt te zijn voor de verbouw van tarwe. Het potentieel geschikte gebied blijkt behoorlijk ongelijk verdeeld te zijn binnen de EG. Vooral in de lidstaten aan de Middellandse Zee is het percentage potentieel gebied gering. Dit kan consequenties hebben voor de landbouwkundige ontwikkelingsmogelijkheden van de regio's binnen de EG. In de tweede fase van de evaluatie zijn voor het potentieel geschikte gebied de water-beperkte en de potentiële tarweopbrengst gesimuleerd. Beide opbrengstniveaus zijn theoretische niveaus, waarbij wordt uitgegaan van een aantal veronderstellingen, zoals een vakbekwame boer met voldoende middelen voor een optimaal gebruik van meststoffen en bestrijdingsmiddelen. Onder potentiële omstandigheden wordt verondersteld dat wateroverlast of watertekort door technische maatregelen is ondervangen. Dit niveau is dan voornamelijk afhankelijk van het weer, zoals de straling en de temperatuur, en de gewasvariëteit. Tabellen en kaarten laten zien dat de water-beperkte en de potentiële tarweopbrengst, ten gevolge van verschillen in bodem en klimaat, behoorlijk variëren binnen de EG. Simulatie van gewasopbrengsten in de landevaluatie is geen doel op zich, maar wordt gebruikt om alternatieven voor landgebruik te verkennen. Uit de gesimuleerde opbrengsten blijkt dat op het huidige tarwe-areaal de produktie nog met 65% kan toenemen onder water-beperkte omstandigheden. Indien wateroverlast of watertekort op het huidige areaal kan worden voorkomen, kan de produktie gemakkelijk worden verdubbeld. Als marginaal land uit produktie wordt genomen, levert dat een beperking op van de tarweproduktie die 40 tot 55% bedraagt van de beperking die kan worden bereikt als het beste land uit produktie wordt genomen.

In de Hoofdstukken 8, 9 en 10 wordt de kwantitatieve fysieke landevaluatiemethode verder ontwikkeld voor de toepassing op bedrijfsschaal. Evaluatie van de effecten van bodemstructuurdegradatie door berijden van het land en grondbewerking staat hierbij centraal. In dit onderzoek neemt het landkenmerk "bodemstructuurtype" een belangrijke plaats in.

In Hoofdstuk 8 worden vier verschillende landeenheden in een lichte zavelgrond onderscheiden op basis van hun bodemstructuurtype, namelijk eenheden met een primaire ploegzool, met een losgemaakte ploegzool, met een herverdichte (secundaire) ploegzool, en met een oud-graslandstructuur. Deze eenheden worden gekoppeld aan verschillende typen van grondbewerking. De eenheden met verschillende structuurtypen kunnen met eenvoudige middelen door veldbodemkundigen worden herkend in het veld. De eenheden worden vervolgens in het veld en in het laboratorium morfologisch en bodemfysisch gekarakteriseerd. Deze gegevens worden ingevoerd in een model dat de waterbeweging in de bodem en de gewasverdamping simuleert en waarmee landhoedanigheden voor de vier eenheden worden berekend. De landhoedanigheden bodemvochttekort, bodemaëratie en bewerkbaarheid worden gepresenteerd in de vorm van kansverdelingen. De verdelingen worden berekend door gebruik te maken van dertigjarige weerreeksen. De verschillen in landhoedanigheden worden geïnterpreteerd als effecten van bodemstructuurdegradatie. Het verschil tussen de eenheden met ploegzolen en die met oud-graslandstructuur geeft een indruk van het maximale effect van structuurregeneratie. Regeneratie blijkt maximaal te leiden tot een stijging van het aantal werkbare dagen met 20%; de vochttekorten worden ongeveer gehalveerd.

In Hoofdstuk 9 wordt nader ingegaan op het proces van kortsluiting van water in lichte, aflopende kleigronden door de aanwezigheid van scheuren en wormgangen (macroporiën). Bovendien wordt een praktische manier gegeven om dit te modelleren. Het water dat wordt kortgesloten, stroomt als vrij water door de bovengrond zonder deze te bevochtigen en infiltreert dan op enige diepte in de ondergrond. Het proces van ondergrondse infiltratie wordt angeduid als 'invanging'. Experimenten in het veld en in het laboratorium worden beschreven om de kortsluiting en de invanging vast te stellen. Een simulatiemodel dat ontwikkeld is om de waterbeweging in gronden zonder macroporiën te beschrijven, is aangepast om de kortsluiting en invanging te incorporeren. De modelaanpassing was nodig om effecten van veranderingen in de bodemstructuur in een vervolgstudie te kunnen onderzoeken. Kortsluiting en invanging blijken een behoorlijke invloed te hebben op het gesimuleerde bodemvochttekort.

In Hoofdstuk 10 wordt het bovengenoemde, aangepaste simulatiemodel toegepast om de effecten van bodemstructuurdegradatie en -regeneratie in een lichte kleigrond te verkennen. Twee landeenheden met verschillende bodemstructuurtypen worden onderscheiden, namelijk een type zoals dat voorkomt in intensief gebruikt jong bouwland, en een type dat men aantreft in oud grasland. Evenals voor de lichte zavelgrond (Hoofdstuk 8) worden de structuurtypen gekarakteriseerd en worden de gegevens gebruikt als invoer voor het aangepaste simulatiemodel. Het structuurtype blijkt een duidelijke invloed te hebben op de relatie tussen de hoeveelheid water die wordt kortgesloten, en de uitdroging van de bodem. Uiteindelijk worden de gesimuleerde landhoedanigheden vergeleken om de maximale invloed van de verandering van de bodemstructuur te schatten. Structuurregeneratie zal in de bestudeerde lichte kleigronden naar verwachting leiden tot gemiddeld 40% meer werkbare dagen, en de gewasopbrengst zal ten minste 5% hoger liggen in 20% van de jaren.

Tenslotte worden in het derde deel van het proefschrift (Hoofdstuk 11) de verschillende fysieke landevaluatiemethoden samengevat. Verschillen in benodigde inspanning en resultaten tussen kwalitatieve en kwantitatieve methoden komen aan de orde. De kwantitatieve methoden hebben beperkingen door inspanningen die nodig zijn om ze toe te passen. De mogelijkheden om potentiële landgebruiksvormen te evalueren zijn echter veel groter dan van de kwalitatieve methoden. De mogelijkheid om nieuwe vormen van landgebruik te verkennen zijn cruciaal in landevaluatie. Toepassing van kwantitatieve methoden is dan ook veelal nodig. De geïntroduceerde, gemengde kwalitatieve/kwantitatieve landevaluatie methode beperkt toepassing van de tijdrovender kwantitatieve methoden tot de relevante gebieden.

In het slothoofdstuk worden verder tekortkomingen van de ontwikkelde evaluatiemethoden beschreven. Zo wordt ingegaan op de onmogelijkheid om met de huidige gegevens de betrouwbaarheid van de resultaten voldoende te beschrijven. Methoden worden aangegeven om de betrouwbaarheid te kwantificeren indien voldoende gegevens voorhanden zouden zijn. Ook wordt vermeld hoe landhoedanigheden die informatie geven over het milieu, kunnen worden geïntegreerd in de huidige landevaluatiemethoden die nog sterk op de produktie zijn gericht. Tenslotte wordt aangegeven hoe de resultaten van de ontwikkelde fysieke landevaluatiemethoden uiteindelijk kunnen worden geïntegreerd in verschillende methoden voor integrale landevaluatie.

CURRICULUM VITAE

Hendricus Albertus Josephus van Lanen werd op 17 maart 1952 geboren te Oeffelt (N.Br.). Na de lagere school doorliep hij van 1964 tot 1969 de HBS-B aan het Sint Chrysostomus Lyceum te Boxmeer. In 1969 begon hij zijn studie bodemkunde en bemestingsleer aan de Landbouwhogeschool in Wageningen. De praktijktijd werd doorgebracht op het Geologisches Landesamt Nordrhein-Westfalen te Krefeld (Duitsland). In 1975 studeerde hij met lof af als landbouwkundig ingenieur met als hoofdvakken regionale bodemkunde en hydrogeologie en met als bijvak klimatologie en meteorologie.

Van 1976 tot 1983 werkte hij als hydrologisch onderzoeker bij de (Geo)hydrologische Hoofdafdeling van het Rijksinstituut voor Drinkwatervoorziening (RID) te Leidschendam. In 1984 werd het RID opgenomen in het nieuwgevormde Rijksinstituut voor Volksgezondheid en Milieuhygiene (RIVM), waar hij werd benoemd in de functie van senior hydroloog bij het Laboratorium voor Bodem- en Grondwateronderzoek. Het onderzoek op het RID en RIVM richtte zich op de winningsmogelijkheden van grondwater voor de drink- en industriewatervoorziening met de nadruk op de beïnvloeding van het landbouw- en natuurbelang en de hydrologische mogelijkheden voor compensatie. Voor dit onderzoek kreeg hij in 1985 een eervolle vermelding van de Stichting Hydrologisch Centrum in het kader van de uitreiking van de Nederlandse Hydrologie-prijs.

In 1984 trad hij in dienst van de Stichting voor Bodemkartering (STIBOKA) als hoofd van de afdeling Bodemgebruik. In 1989 werd de STIBOKA opgenomen in het nieuwgevormde Staring Centrum (SC), waar hij de functie hoofd van de afdeling Landevaluatiemethoden ging bekleden. Op de STIBOKA en het SC bestond zijn taak in het verrichten van onderzoek, alsmede het leiding geven aan onderzoek naar de ontwikkeling van landevaluatiemethoden, waarbij het gebruik van kennissysstemen, simulatiemodellen en de koppeling met ruimtelijke gegevens in een geografisch informatiesysteem op verschillende kaartschalen centraal stonden. Dit onderzoek vormt het onderwerp van het proefschrift.

Vanaf 1976 heeft hij als (co-)auteur aan ruim 70 rapporten, boeken en publikaties meegewerkt. In 1989 heeft hij als editor gefungeerd van de proceedings van een EG-workshop over "Application of computerized EC Soil Map and Climate Data".

Op 1 maart 1991 is hij in dienst getreden als universitair hoofddocent hydrogeologie bij de vakgroep Hydrologie, Bodemnatuurkunde en Hydraulica van de Landbouwuniversiteit.