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Land use systems research on strongly weathered soils in south and south-east Brazil

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Landgebruikssystemen op sterk verweerde gronden in zuid en zuid-oost Brazilië

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR AAN DE UNIVERSITEIT UTRECHT OP GEZAG VAN DE RECTOR MAGNIFICUS, PROF. DR. H.O. VOORMA INGEVOLGE HET BESLUIT VAN HET COLLEGE VOOR PROMOTIES IN HET OPENBAAR TE VERDEDIGEN OP DONDERDAG 21 SEPTEMBER 2000 DES MORGENS TE 10.30 UUR

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PART I

INTRODUCTION

1. LAND USE SYSTEMS RESEARCH ON STRONGLY WEATHERED SOILS IN BRAZIL: CHALLENGES AND STUMBLING BLOCKS

1.1 Strongly weathered soils

Strongly weathered soils are typically deep, well drained, friable, red or yellow soils with very small nutrient reserves. Even though most of these soils are chemically poor, they are generally capable of supporting agricultural production, forming the world's greatest reserve of potentially arable land (Sanchez, 1981, 1997). Therefore it is sensible to understand their characteristics and how crops perform when grown on them.

According to Sanchez (1981), regions with strongly weathered soils occupy approximately 16.6M km^2 world-wide, which corresponds to 41% of the global arable area. About 45 % of this area occurs in Latin America, mostly in Brazil and another 40 % in tropical Africa. Other major occurrences are found in South East Asia and Oceania.

In Brazil, a considerable part of these soils is (still) under natural vegetation (Nepstad et al., 1997), predominantly the tropical rain forests in the Amazon basin and the dense vegetation of herbaceous species with evergreen and semi-deciduous shrubs, called cerrado, mainly in central Brazil. Natural grasslands, forests and cerrado that once covered strongly weathered soils in the south and south-east have practically disappeared. "Reclamation" has resulted in success stories (Goedert & Lobato, 1986, Lopes, 1996), giving Brazil a prominent place among the world's greatest producers of agricultural goods; but land degradation, related to inadequate management has also been reported (Klamt et al., 1983; Resende et al., 1996), as well as complete failures (Demattê, 1988; Serrão et al., 1996).

A combination of factors such as government incentives, technological development, quest for land for poor rural population, land property regulations, road building in formerly inaccessible regions and the wealth in valuable timber are the cause that natural ecosystems on strongly weathered soils are being destroyed at an astonishing rate to make place for crop-livestock-forestry production (Carvalho & Brown, 1996; Nepstad et al., 1997). Conservative estimates of Nepstad et al. (1997) indicate a rate of natural vegetation cleared of 20 000 $km^2\,year^{-1}$ in the Brazilian cerrado region, over the period from 1988 to 1991, and some 15 000 $km^2\,year^{-1}$ in the tropical forest region (1992 - 1994). Clearance rates have probably increased since then. These huge transformations are destroying the local ecosystems and are also thought to have great environmental impact at regional, continental and global level (Setzer & Pereira, 1991; Klink et al., 1993; Houghton, 1996). Settlers, loggers and some politicians claim that this is necessary to increase economic wealth and food production and to decrease migration from the country to the (shanty towns of) major cities. Others suggest that a more rational use of the lands that are already being explored would be more than sufficient to invert rural exodus and to feed the Brazilian population far into the 21st century (Lopes, 1996).

The increasing concern with the environmental impact of agriculture, the need to stop the progressive disappearance of unique natural ecosystems and the need to turn agriculture into a more profitable business call for well balanced rational choices. Systematic research is necessary to explore the potentials of alternative land uses that can provide sustainable incomes and prevent the waste of natural resources.

1.2 Land evaluation

Land evaluation is "the process of assessment of land performance when used for specified purposes in order to identify and make a comparison of promising kinds of land use" (FAO,1976). The basic configuration for which land performance is assessed is a *land use system*. This is a combination of one *land unit* with one *land utilisation type* (Driessen & Konijn, 1992). A land unit is an area of land that can be considered homogeneous as far as the requirements of its use are concerned. A land utilisation type is defined by a set of technical specifications of land use in a physical, social and economic setting (FAO, 1976).

Until recently, the principal tools to conduct land use systems analysis were qualitative methods, based on expert knowledge and parametric methods, based on empirically determined relations between land characteristics and the performance of land use systems. In the 1980's, quantified land evaluation (QLE) using deterministic models was introduced as a new paradigm in land use systems analysis, to replace the vague subjective terminology of qualitative methods and the excessively simplified parametric models (Van Diepen, 1983; Driessen, 1988; Dumanski & Onofrei, 1989; Van Diepen et al., 1991). Some of the main characteristics of this new approach are: (1) Complex land use systems are divided into basic elements (e.g. soil horizons, components of a growing crop); and (2) the dynamics of each element (e.g. on a daily basis) and the interactions between them are described in terms of mathematical equations, that represent causal relationships (deterministic).

A toolbox of models that quantify the extent to which different land units correspond to the requirements of alternative land uses, could be called a Quantified Land Evaluation System (QLES). Examples of models to be integrated in QLES refer to e.g. environmental impact, crop yield potential under different levels of management, labour opportunities and cost-benefit analyses. A good QLES must also take account of the spatial variability of land characteristics: it makes use of a Geographical Information System (GIS).

Although prototypes with some characteristics of QLES have appeared (e.g. Meijerink, 1988, Johnson et al., 1994; Mantel & Van Engelen, 1997), it is questionable if comprehensive and reliable QLES will become available for practical purposes in the near future. Some of the major problems related with its development and use are:

a - The socio-economic environment cannot easily be quantified.
b - Biophysical processes are very complex.
c - Required data are insufficiently available.
d - Spatial variation is difficult to assess.

a) Socio-economic environment. Social and cultural aspects of land are related to religion, status, tradition, taste and many other factors that can hardly be quantified, but which have long been underestimated as crucial for success or failure of land use plans (e.g. Röling, 1997). The economic environment cannot be restricted to the target area. Prices depend on the international market, which in turn depends on world-wide climatic, economic and political situations. FAO (1976) and Driessen (1988) suggested a two stage approach to avoid excessive complications. In the first stage, e.g. natural resource experts and agronomists determine what is *physically* possible. The results are passed on to stakeholders, sociologists and economists, who, in the second stage, use their methods to derive the most promising options for land use. A more integrated approach with interactions or feedback between the stages is also possible. This thesis only addresses biophysical aspects related to crop production.

b) Biophysical processes. One of the core components of a QLES would be a mathematical model to calculate crop yield potentials. Truly deterministic models that rely entirely on biological, chemical and physical laws are not fit for land use systems analysis because such models require very detailed data that cannot be made available for large regions at reasonable costs. Besides, basic processes such as plant water uptake and the partitioning of assimilates among crop organs are still poorly understood (Montheith, 1996). So-called "summary models" (Rabbinge & De Wit, 1989; Dumanski & Onofrei, 1989; Driessen, 1996) attempt to circumvent these restrictions by describing only the most relevant processes and substituting complex (or poorly understood) processes by simple descriptive equations. These descriptive equations are often derived by regression techniques and should be validated[1] and/or calibrated[2] before applied to new situations. Collection of test data is expensive and time consuming. The challenge is to develop equations that combine simplicity with a wide range of application.

c) Data requirements. Even summary models need a considerable amount of input data before they can be applied. An indicative list for crop growth modelling is given in table 1.1. This list applies to situations where production is conditioned solely by climate and soil water availability. Many more data are necessary when other yield limiting and reducing factors such as plant nutrition, diseases etc... are taken into account. Even the data of table 1.1 cannot easily be obtained. For example, meteorological data are measured world wide, but observation density is far from uniform. Many developing countries have few reliable stations. Crop parameter values required for modelling are becoming increasingly available in published literature, but their application is risky, because each specific crop variety may have its specific set of parameters, many of which also seem to be site dependent. For spatial modelling, soil data should be available from soil maps and the accompanying reports. However, these are often strongly focussed on classification which may affect their utility for land evaluation because (1) diagnostic criteria of soil classification systems are primarily related with the (presumed) formation of soils and not necessarily correlated with land qualities, and (2) classification systems require standard laboratory analyses of soil samples. Prescribed methods involve crushing, sieving, removal of carbonates, organic matter and iron oxides and do not observe the pedosphere experienced by a crop. Soil water data cannot usually readily be obtained from survey reports. So-called transfer functions have been proposed to estimate

Table 1.1 Example of input data for summary crop growth models

Climate/weather data (usually daily)

- Day length (calculated from date and geographic position)
- Incoming photosynthetically active radiation (PAR)
- Incoming total radiation
- Temperature (minimum, maximum, average)
- Precipitation
- Reference or potential evapo(transpi)ration
- Wind speed
- Air humidity

Crop data

- Type of crop (C3 or C4);
- Possibility of root respiration (and moisture uptake) in anaerobic conditions (usually 1 for crops with airducts such as rice and 0 for other crops);
- Genetically defined maximum rooting depth;
- Efficiency coefficients (values between 0 and 1) for transformation of primary photosynthates to structural material of resp. leaf, root, stem and storage organ;

Parameters for equations to describe the following (functional) relationships:

- Phenologic development rate (from germination to maturity) as function of environmental factors (e.g. temperature, day length, moisture sufficiency);
- Leaf development rate (from emergence to senescence) as function of environmental factors (e.g. temperature, moisture sufficiency);
- Photosynthesis rate as function of absorbed PAR, temperature and moisture sufficiency;
- Absorbed PAR as function of incoming PAR and leaf area index;
- Change of rooted depth as function of temperature, moisture sufficiency, etc...;
- Maximum transpiration rate as function of reference transpiration rate and e.g. LAI;
- Actual transpiration rate as function of maximum transpiration rate and soil moisture;
- Specific leaf area as function of phenological development stage;
- Partitioning of assimilates over leaves, roots, stems and storage organs; function of phenological development stage;
- Relative respiration rates of leaves, roots, stems and reproductive organs; function of temperature.

Soil data

- Initial soil moisture content (may vary with depth);
- Initial depth of groundwater;
- Maximum rootable depth (as limited by soil properties);
- Upper and lower limits of soil water availability (may vary with depth), or:

Parameters of equations to describe:

- Soil water potential as function of soil water content (may vary with depth);
- Soil hydraulic conductivity as function of soil water content (may vary with depth);

such difficult data on the basis of routinely measured properties, but with varying success (Van den Berg et al., 1997).

d) Spatial variability. Observed soil and climate data refer to discrete points in space and time. There are several ways to extrapolate such point data to areas, as would be necessary for QLE (e.g. Burrough & McDonnell, 1998). Mapping units of classical choropleth maps are obtained by lumping together sites with similar characteristics. Interpolation methods may be used to form isorithmic maps. It is impossible to give an exact description of the continuum of land characteristics, but it is possible to assess the expected variance or error. In spite of the availability of straightforward methodologies, most commonly, surveys pay little attention to errors and uncertainties in their products. Using so-called representative soil profiles as a major source of information on soil mapping units is therefore questionable. Average values are permitted in some cases, but may lead to absurd artefacts when contrasting soils occur within a mapping unit.

The aforementioned problems have long been recognised (Beckett & Webster, 1971, Passioura, 1973; Varcoe, 1990; Van Diepen et al., 1991; Burrough, 1993), but their persistence seems to have been underestimated. Today, the utility of simplified deterministic models for predictive purposes is a subject of controversy. The concept has been severely criticised by some authors (e.g. Passioura, 1996); others emphasise achievements (Boote et al., 1996). A somewhat ambivalent impression is given by Van Diepen et al. (1998), whereas Driessen (1997) seems to regard the problems as interesting challenges. Few studies have been done so far to obtain a more objective image of to which extent errors and uncertainties in data and models affect the relevance of QLE.

1.3 Objectives

The general objectives of this study are: (1) to increase the knowledge of the agricultural properties of strongly weathered soils and their spatial variability, and (2) to explore the potential of summary crop growth models together with existing soil maps in modern (quantified) land use systems analysis at regional level, in particular on strongly weathered soils.

1.4 Research strategy and structure of this thesis

The research strategy adopted was to critically analyse some aspects that were expected to have greatest impact on the quality of bio-physical land use systems analysis in regions of strongly weathered soils, rather than focussing on details or assessing the entire process superficially. Therefore the research was conducted as a set of case studies. Research areas were selected in three regions of Southeast and South Brazil.

Many pragmatic choices had to be made. The study regions were selected in (sub)tropical Brazil because it has the world's major occurrences of strongly weathered soils (ISSS Working Group RB, 1998b), for which alternative uses and/or nature preservation are subjects of debate as described in section 1.1. Reasons to choose the study regions in (South)east Brazil are (1) co-operative scientific staff from nearby research institutes; (2) access to weather data and on-farm yield and management records of reasonable quality; (3) good infrastructure; and (4) availability of basic documents including soil maps at semi-detailed or reconnaissance level. It is expected however, that some findings of this study will also be relevant to other regions with similar physiographic conditions in South America and sub-Saharan Africa (Sanchez, 1997). Sugarcane and soybean were selected as test-crops, because of their agricultural and economic importance and the availability of research data and yield records.

Figure 1.1 indicates the research topics of this thesis in relation to the information stream from data collection to the prediction of yield potentials by crop growth models. The thesis consists of four parts which were subdivided in 13 chapters, each with its specific objectives. It is structured as follows.

Part I, is the introductory part, containing this general introduction (chapter 1). Chapter 2 presents a brief review on strongly weathered soils and identifies knowledge gaps in relation to their use potential and management. A brief description of the study regions is given in chapter 3.

Part II Discusses the variability of the (apparently homogeneous) soilscapes of the study regions and its relation to the quality of soil maps. Geostatistical methods are used in chapter 4 to quantify the spatial scales of variation of major physical and chemical soil characteristics and addresses the question if spatial patterns detected are characteristic for areas with strongly weathered soils. Chapter 5 evaluates the adequacy of existing semi-detailed and reconnaissance soil maps of the regions for land use systems research.

Soil water relations and related transfer functions are addressed in part III. Chapter 6 discusses the applicability of simplified water availability concepts to the strongly weathered soils of the study regions. Chapter 7 investigates if key soil-water parameters, which are difficult to measure but necessary for input in crop growth models, can be predicted adequately by transfer functions on the basis of readily available data.

Part IV discusses summary modelling approaches to selected bio-physical processes and the applicability of a crop growth model to land uses systems in the study regions. Chapter 8 reviews how crop water uptake is currently accounted for in summary models of different schools, and looks into the backgrounds of discrepancies. Chapter 9 compares three of these approaches to check if different methods provide disparate results; and suggests improvements. Chapter 10 discusses another important feature of crop growth models, which is the method to describe the partitioning of assimilates among different parts of the crop (roots, leaves, stems etc..) over the growing season. A new approach is proposed and primary tests are conducted for soybeans and sugarcane. Chapter 11 compares biophysical water-limited yield potentials, calculated by a crop growth model (adapted to the findings of the previous chapters) with on-farm yield records from the study regions. Ideally, the differences between model results and recorded data (so-called yield gaps) would be caused by limiting or reducing factors that are not considered by the model, such as nutrient insufficiency, pests and harvest losses. Chapter 12 addresses the question to which extent errors/uncertainties related to water availability assessment in the model or in the input data (originating from unresolved spatial soil variability) may also contribute to inferred yield gaps.

Part V (chapter 13) discusses the results obtained in relation to the general objectives of this thesis and presents the conclusions

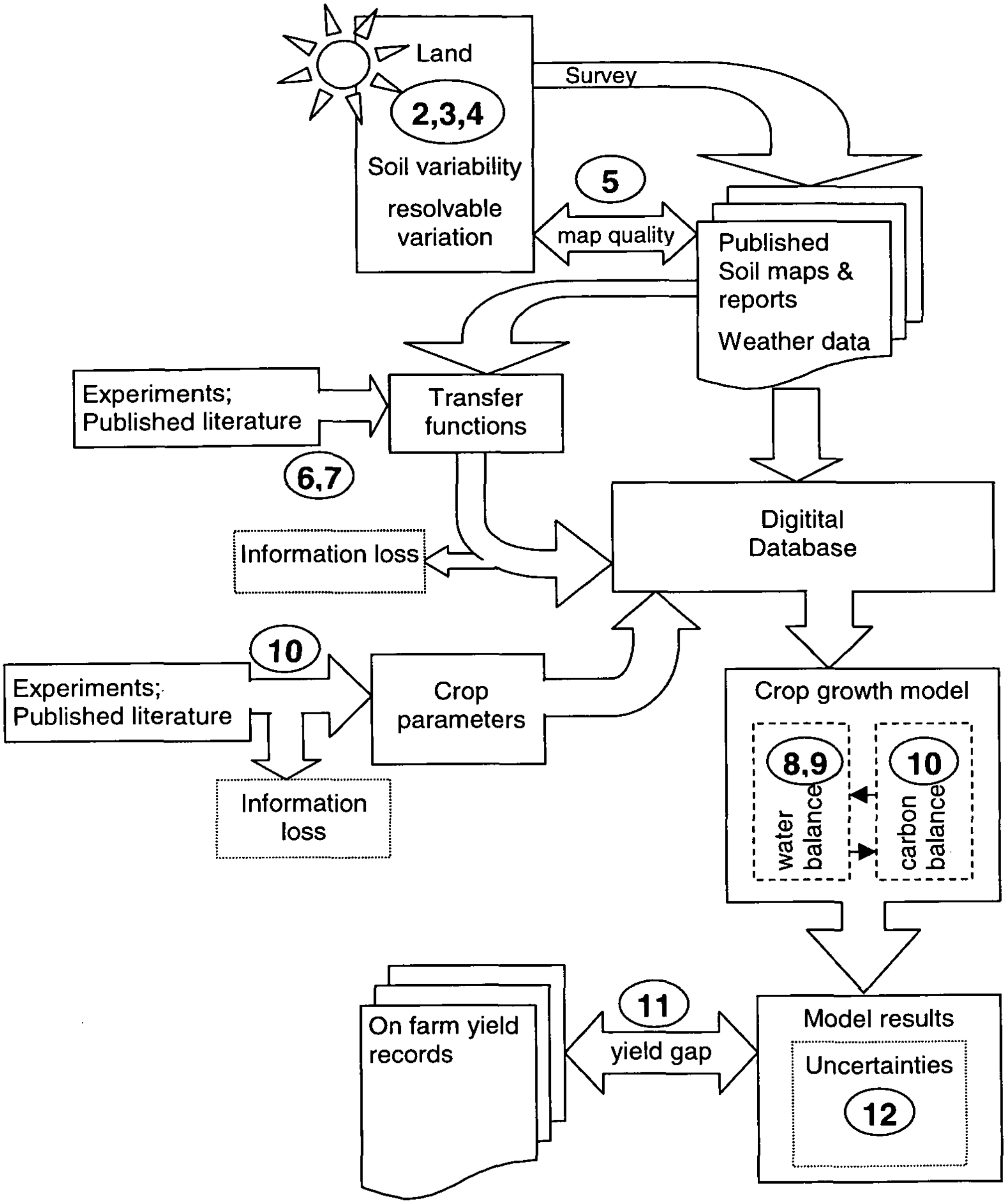


Figure 1.1 Topics addressed in this study in relation to the information stream by application of crop growth models in regional land use systems analysis. Numbers in ovals refer to chapters of this thesis

[1] Validate: to prove by means of scientific tests that information is correct. In modelling jargon the term is often used as "to verify that model results show reasonable agreement with independently obtained data".

[2] Calibrate: adjust model parameters by running the model with different values until an optimum fit between observed and calculated results is obtained

2. STRONGLY WEATHERED SOILS IN BRAZIL

2.1 Working definition

Strongly weathered soils are defined in this text as: deep red or yellow soils with low activity clays (CEC clay < 16 cmol(+) kg^{-1}), virtually without weatherable minerals. Only strongly weathered soils that were formed under well drained conditions are considered. According to the World Reference Base for Soil Resources (ISSS Working Group RB, 1998a), these soils are classified as Ferralsols, Acrisols, Lixisols, Nitisols and ferrallic Arenosols.

2.2 Genesis

Strongly weathered soils are the result of intense chemical weathering of parent rock whereby soluble silica and basic cations are removed by percolating water. These processes are promoted by warm and humid conditions. Their persistence for, say, more than 100 000 years leads to a mineral composition with predominance of low charged 1:1 clay minerals, mainly kaolinite and sesquioxides (oxides, hydroxides and oxihydroxides of iron and aluminium). Sand-sized quartz grains inherited from the parent material remain in the profile because they are very resistant to weathering. Eventually, weatherable minerals of the parent material disappear and the soils become chemically and physically stable. Vertical differentiation that may have characterised earlier stages of formation is largely undone by long term biological activity throughout the soil, mainly by ants and termites. Advanced age is also reflected by the predominate occurrence on gently undulating lands.

The soils are not exclusive to any particular substratum, but their formation is enhanced on easily weatherable materials, such as most sedimentary and volcanic rocks. On more resistant materials, such as gneiss and granite, they are confined to extremely old surfaces, such as the African pre-Cambrian shield.

The characteristic red and yellow colours of strongly weathered soils reflect the type and content of iron oxi(hydr)oxides. Yellowish red soils contain principally goethite whereas dusky red colours are indicative of hematite and magnetite (Schwertmann, 1985). Variations in colour, soil texture, type of B horizon, degree of weathering, contents and types of sesquioxides (gibbsite, goethite, magnetite, hematite etc...) and silicates (kaolinite, halloysite, chlorite) are related to differences in Jenny's (1941) factors of soil formation: climate, organisms, relief, parent material and time. Causal relations are often difficult to elucidate, because during their time of formation these soils have been influenced by different climatic conditions with different kinds of organisms, parent materials have been reworked and relief inversions may have occurred (Oliveira et al., 1992; Muggler, 1998).

2.3 Classification

Classification of strongly weathered soils has been a controversial topic for soil taxonomists during several decades and remains so until today. This is reflected by frequent modifications of classification systems and the different diagnostic criteria used by different systems. In this thesis, the soil classification in use in Brazil (Camargo et al., 1987; Oliveira et al., 1992) is used as the reference, because the legends of the soil maps of the regions studied are based on it. Table 2.1 outlines the taxonomy of strongly weathered soils. Relevant diagnostic horizons of the system in use in Brazil, the FAO Legend (FAO, 1990) and Soil Taxonomy (Soil Survey Staff, 1998) are correlated in table 2.2. Table 2.3 gives a taxonomic comparison of strongly weathered subsurface horizons and table 2.4 compares subsurface horizons with pronounced clay differentiation.

2.3.1 Soil classification in use in Brazil

The soil classification system in use in Brazil (Camargo et al., 1987; Oliveira et al., 1992) classifies strongly weathered soils as Latosols, Structured Dusky Red and Brown Earths, Podzolics, and Quartzose Sands.

Latosols represent the fine textured soils in the most advanced stage of weathering. They have a latosolic B horizon characterised by: very low cation exchange capacity, few weatherable minerals, and little vertical differentiation. Latosols are well drained, yellow to dusky red soils with little vertical differentiation. They have a strong micro-structure with sand and silt-sized aggregates consisting of clay (kaolinite) particles cemented by sesquioxides. Macro-structure is weak or absent. The consistence is slightly sticky and slightly plastic when wet, friable or very friable when moist and slightly hard when dry, even if the texture is very fine clayey.

Structured Dusky Red and Brown Earths have a textural B horizon with moderate to strong blocky or compound prismatic structure and associated clay skins. Texture is clayey or very fine clayey throughout. These soils are well drained and have homogeneous dark brown to dusky red colour. Soil consistence in the textural B horizon is typically firm when moist, slightly sticky when wet and hard when dry. With increasing depth, the textural B horizon usually changes gradually into a horizon with similar properties as a latosolic B horizon. As a rule, these soils are formed on rich parent materials, e.g. basalts (Oliveira et al., 1992).

Strongly weathered Podzolics have a textural B horizon, with distinctly higher clay content than the overlying horizon(s), but usually lack a well-developed macrostructure. Consistence of the textural B horizon is friable or firm when moist and often harder when dry and stickier when wet than associated Latosols, but usually becomes similar to a latosolic B with increasing depth. Many Podzolics are moderately well drained due to stagnation of water on top of the textural B horizon after receiving heavy rainfall (Oliveira et al.,1992). Some mottling may reflect this.

Strongly weathered soils with a sandy texture are classified as Quartzose Sands.

Table 2.1 Summarised taxonomic definitions of strongly weathered soils in the study areas. Definitions according to Camargo et al. (1987), Oliveira et al. (1992) and Oliveira & Prado (1984)

Soil classes at first two hierarchical levels

LATOSOLS: Mineral soils, not hydromorphic, with latosolic B horizon.

- **Dusky Red Latosols**: Dusky red to dark reddish brown (B horizon with hue redder than 4YR, value ≤ 3, chroma ≤ 6); related to high content of Fe_2O_3 (180-400 $g\,kg^{-1}$)*, strong magnetic attraction, Ki (molecular ratio SiO_2/Al_2O_3): 0.2-2.0
- **Dark Red Latosols**: Dark red to dark reddish brown, related to medium content of Fe_2O_3 (80-180 $g\,kg^{-1}$)*, weak magnetic attraction; Ki 0.2-2.2
- **Red-Yellow Latosols**: Red, yellowish red to strong brown, related to small content of Fe_2O_3 (70-110 $g\,kg^{-1}$)*; virtually no magnetic attraction; Ki < 1.5; molecular ratio $SiO_2/(Fe_2O_3+Al_2O_3)<1.4$

*Applied to soils with clay content ≥ 350 $g\,kg^{-1}$. For medium textured soils, the Al_2O_3/Fe_2O_3 molecular ratio is used as a distinctive criterion; e.g. 3.14 is the upper limit for Dark Red Latosols.

STRUCTURED DUSKY RED and BROWN EARTHS: Mineral soils, not hydromorphic, clayey. Textural B horizon has moderate to strong blocky or compound prismatic structure. Associated clay skins are at least common and moderately developed. Low clay activity. Small clay increase from A to B horizon. Red or brown colour reflect medium to high Fe_2O_3 content.

- **Structured Dusky Red Earths:** Dark reddish brown, dusky red, reddish brown, dark red to red. Fe_2O_3 ≥ 150 $g\,kg^{-1}$; $TiO_2 \geq 15$ $g\,kg^{-1}$; weak or no magnetic attraction; Ki 0.9-2.3
- **Structured Brown Earths** : Brown, dark brown, strong brown, reddish brown to yellowish red. Medium to high content of Fe_2O_3 (>100 $g\,kg^{-1}$), no magnetic attraction; Ki 1.7-2.1

PODZOLICS: Mineral soils, not hydromorphic; any A and/or E horizon; not plinthic. Textural B horizon lacks distinctive features of Planosols. N.B. According to consulted documents, all podzolics of the study regions have low clay activity (i.e. CEC clay < 240 $mmol_c\,kg^{-1}$), indicated as Podzolics Tb.

- **Dark Red Podzolics**: Red to dark reddish brown;
  $37.5+(0.0625*clay\ (g\,kg^{-1})) \leq Fe_2O_3 \leq 150\ g\,kg^{-1}$ and $TiO_2 \leq 17\ g\,kg^{-1}$

  Red Yellow Podzolics: Red, yellowish red to strong brown; $Fe_2O_3 \leq 37.5+(0.0625*clay)g\,kg^{-1}$

QUARTZOSE SANDS: Soils with AC profile formed on quartzose sands.

Subdivisions at third level

Intergradational properties, e.g. Red Yellow Latosols, intergrade with Podzolics..
Trophic character of B horizon:
eutrophic: base saturation $\geq$ 50%
dystrophic: base saturation < 50% and Al saturation < 50%; **allic**: Al saturation $\geq$ 50 %
Type of A horizon:
weak: weakly structured or structureless, with colour value moist > 5 and organic C content < 5.8 $g\,kg^{-1}$
moderate: as ochric of FAO (1990), excluding weak A
prominent: as umbric of FAO (1990). Soils with a very thick prominent A horizon are classified as **humic**
chernozemic: as mollic of FAO (1990)
Texture:
sandy: sand + loamy sand of FAO (1977)
clayey: 350 $\leq$ clay content $\leq$ 600 $g\,kg^{-1}$; **very fine clayey**: clay content > 600 $g\,kg^{-1}$
medium: rest group. Oliveira & Prado (1984) distinguish **sandy medium**: [clay cont. < 200 $g\,kg^{-1}$ or (clay cont.< 250 $g\,kg^{-1}$ and content of coarse sand > fine sand)] and **fine medium**: finer than sandy medium.
Podzolics: texture class of both A (or E) and Bt horizons are indicated separated by "/", e.g. sandy/clayey.

Table 2.2 Correlation of possible diagnostic horizons in strongly weathered soils as defined by the FAO Legend (FAO, 1990), Soil Taxonomy (Soil Survey Staff, 1998) and the soil classification system in use in Brazil (SNLCS, according to Camargo et al., 1987)

Concept	FAO Legend	Soil Taxonomy	BRAZIL - SNLCS
Thick dark mineral surface horizon with high organic matter content and high base saturation	Mollic A horizon	Mollic epipedon	Chernozemic A horizon
Thick dark mineral surface horizon with high organic matter content and low base saturation	Umbric A horizon	Umbric epipedon	Prominent A horizon or humic A horizon (strongly developed)
Weakly developed surface horizon	Ochric A horizon	Ochric epipedon	Moderate A horizon or weak A horizon (very weakly developed)
Eluvial horizon	Albic E horizon	Albic horizon	Albic E horizon
Subsurface horizon with clay accumulation	Argic B horizon	kandic horizon or argillic horizon (with clay films)	Textural B horizon
Strongly weathered subsurface horizon	Ferralic B horizon	Oxic horizon or kandic horizon (with marked clay accumulation)	Latosolic B horizon

At the second level in the hierarchy of the soil classification system in use in Brazil, colour, total Fe_2O_3 content and the molar ratio Fe_2O_3/Al_2O_3 are used to distinguish soil classes. At lower levels, the soils are differentiated by type of A-horizon, base- and aluminium-saturation of the B-horizon, and soil texture.

The system described above was recently officially replaced by the Brazilian System of Soil Classification (EMBRAPA, 1999). Major differences for strongly weathered soils are in the nomenclature of soils with a textural B horizon, which are now accommodated in Argisols (most Podzolics with low activity clays) and Nitosols (most structured Earths). Some definitions were sharpened and others were rather drastically changed. For example, a latosolic B horizon according to EMBRAPA (1999) has a cation exchange capacity $<17\,cmol_c\,kg^{-1}$ clay without correction for organic matter. Little is known so far on the practical implications of these changes.

Table 2.3 Comparison of diagnostic criteria for strongly weathered subsurface horizons according to the FAO Legend (FAO, 1990), Soil Taxonomy (Soil Survey Staff, 1998) and the soil classification system in use in Brazil (SNLCS, according to Camargo et al., 1987)

	FAO Legend	**Soil Taxonomy**	**BRAZIL-SNLCS**
Name	ferralic B Horizon	1) oxic or 2) kandic horizon	latosolic B horizon
Texture	sandy loam or finer and ≥80 g kg^{-1} clay in fine earth	1) sandy loam or finer 2) loamy very fine sand or finer	sandy loam or finer
Thickness	≥30 cm	≥30 cm	≥50 cm
Cation exch. capacity	≤16 $cmol_c$ kg^{-1} clay or ECEC ≤12 $cmol_c$ kg^{-1} clay after correction for organic matter	≤16 $cmol_c$ kg^{-1} clay and ECEC≤12 $cmol_c$ kg^{-1} clay	<13 $cmol_c$ kg^{-1} clay after correction for organic matter
Weatherable minerals	<10% in 50-200 μm fraction	1) <10% in 50-200 μm fraction	<4% in 50μm-2 mm fraction
Silt/clay ratio	≤0.2	–	<0.7
andic properties	not allowed	not allowed	not allowed
Rock structure	<5% by volume	1) <5% by volume, unless lithorelicts are coated with sesquioxides	<5% by volume
Others	water dispersible clay <100 g kg^{-1}	Regular decrease in organic C content with depth and no fine stratification. 2) Underlies a considerably coarser textured surface horizon. 1) applies to oxic only 2) applies to kandic only	Lacks the set of properties that characterises a textural B horizon

2.3.2 FAO legend of the soil map of the world

The Revised Legend of the Soil Map of the World (FAO, 1990), here abbreviated as FAO Legend, divides well drained strongly weathered soils among 6 major soil groupings: Ferralsols, Nitisols, Acrisols, Lixisols, Cambisols and Arenosols.

Ferralsols correspond roughly with the Latosols of the Brazilian system. They have a ferralic B horizon characterised by: very low cation exchange capacity, few weatherable minerals, very small silt content, small content of water dispersible clay, and little vertical differentiation.

Table 2.4 Comparison of diagnostic criteria for subsurface horizons with clay accumulation according to the FAO Legend (FAO, 1990), Soil Taxonomy (Soil Survey Staff, 1998) and the soil classification system in use in Brazil (SNLCS, according to Camargo et al., 1987)

	FAO Legend	**Soil Taxonomy**	**BRAZIL-SNLCS**
Name	argic B horizon	argillic horizon	Textural B horizon
Texture	sandy loam or finer and clay content >80 g kg^{-1}	_	_
Vertical clay differentiation	If clay content of overlying horizon <150 g kg^{-1} then ≥30 g kg^{-1} more clay than overlying horizon.	If clay content of overlying horizon <150 g kg^{-1} then ≥30 g kg^{-1} more clay than overlying horizon.	If clay content of overlying horizon <150 g kg^{-1} then clay ratio (Text.B)/(overlying hor) > 1.8
	If clay content of overlying horizon 150-400 g kg^{-1} then clay ratio {(argic B)/(overlying hor)} ≥1.2	If clay content of overlying horizon 150-400 g kg^{-1} then clay ratio {(argillic B)/(overlying hor)} ≥1.2	If clay content of overlying horizon 150-400 g kg^{-1} then clay ratio (Text.B)/(overlying hor) ≥ 1.7
	If clay content overlying horizon >400 g kg^{-1} then ≥80 g kg^{-1} more clay than overlying horizon.	If clay content of overlying horizon ≥400 g kg^{-1} then ≥80 g kg^{-1} more clay than overlying horizon.	If clay content of overlying horizon >400 g kg^{-1} then clay ratio (Text.B)/(overlying hor) > 1.5
			These requirements are waived if an E horizon is present or if B horizon has blocky or prismatic structure and clay skins exceed few and weak.
Vertical distance for clay increase:	≤ 30 cm if clay skins are evident; else ≤15cm	≤ 30cm	_
Thickness:	>15 cm and > 1/10th of the sum of all overlying horizons	if texture coarse loamy or finer: ≥7.5 cm and at least 1/10th of overlying horizons else: ≥ 15 cm	if base below 150cm then thickness ≥15cm else: if texture sandy: ≥15cm if texture loamy or finer: ≥7.5cm and at least 1/10th of overlying horizons
Thickness of overlying horizons	>5 cm if transition is abrupt. Else >18 cm	_	_
Others	Lack the set of properties that characterise a ferralic B horizon.	Evidence of clay illuviation: clay films or oriented clay bridging or oriented clay bodies.	_

Nitisols, Acrisols and Lixisols have an argic B horizon and they contain more weatherable minerals, more water dispersible clay or more silt than Ferralsols. The central concept of Nitisols corresponds roughly with Structured Earths of the system in use in Brazil. The argic B horizon of Nitisols is composed of "nutty" angular blocky structural elements with shiny faces. The difference between Acrisols and Lixisols is that Lixisols present a base saturation $\geq$ 50 % throughout the argic B horizon. Together, they correspond roughly with strongly weathered Podzolics of the system in use in Brazil.

Strongly weathered soils with a sandy texture are classified as ferrallic Arenosols and those that lack one or more diagnostic properties of the above named major soil groupings are keyed out as Cambisols (e.g. strongly weathered soils lacking an argic B horizon and having either silt/clay ratio > 0.2 or water dispersable clay $\geq$ 100 g kg^{-1}).

2.3.3 Soil Taxonomy

Soil Taxonomy (Soil Survey Staff, 1998) classifies most strongly-weathered soils as Oxisols. Oxisols have either an oxic horizon or a kandic horizon overlain by a clayey surface horizon. The oxic and kandic horizon together correspond roughly with the latosolic B horizon of the Brazilian system and the ferralic B horizon of the FAO Legend. Strongly weathered soils with an argillic horizon and those with less than 400 g kg^{-1} clay in a surface horizon that overlies a kandic horizon key out as (1) Mollisols if a mollic epipedon is present and base saturation is $\geq$ 50 % throughout the soil, or (2) Ultisols if base saturation in the subsoil is less than 35%, or else (3) Alfisols.

2.3.4 World reference base for soil resources (WRB)

The World reference base for soil resources (ISSS Working Group RB, 1998a) - shortly WRB - is based on the FAO Legend (FAO, 1990). The reference soil groups - Ferralsols, Nitisols, Acrisols, Lixisols, Cambisols and Arenosols – have the same central concept as their homonyms of the FAO Legend, but some definitions are different. The most important ones are:

- The WRB has introduced a nitic horizon, which is *"a clay-rich subsurface horizon with as its main features a moderately to strongly developed polyhedric or nutty structure with many shiny ped faces, which cannot or only partially be attributed to clay illuviation"*. The nitic horizon is diagnostic for Nitisols and lacking in Ferralsols. According to Oliveira & Van den Berg (1996), this amendment may cause a shift of many Brazilian Dusky Red Earths from Ferralsols of the FAO Legend to Nitisols of the WRB.

- In contrast to the ferralic B horizon of the FAO Legend, the ferralic horizon of the WRB does not necessarily present a silt/clay ratio $\leq$ 0.2 and the criterion with respect to water dispersible clay is not applied when CEC is extremely low. Brazilian soil scientists consider these criteria of the FAO Legend much too restrictive (Oliveira & Van den Berg, 1996). Oliveira & Van den Berg (1996) expect that as a consequence, many Brazilian Latosols that are classified as Acrisols, Lixisols or Cambisols of the FAO Legend will shift to Ferralsols of the WRB.

2.4 Properties and management

2.4.1 Physical properties

Latosols have excellent physical properties. In their natural condition they have good internal drainage, they are easily workable and pose no physical barrier to plant roots. These properties are somewhat less favourable, but usually not restrictive, in Structured Earths. Podzolics are more problematic. They are sensitive to erosion, especially when clay differentiation is pronounced (Lepsch, 1983). Texture of strongly weathered soils ranges from sandy to very fine clayey, but silt contents are usually small, say less than 150 $g\,kg^{-1}$.

Crop water stress is frequently observed, even though strongly weathered Brazilian soils occur predominantly in regions with annual rainfall > 1300 mm. It is particularly conspicuous during so-called veranicos: dry spells of, say, two weeks during the hot rainy season (Resende et al., 1996a). Strongly weathered soils have particular moisture retention characteristics, related to a bimodal pore size distribution associated with their strong micro-structure (Chauvel et al., 1991). This makes them act like sands when wet, and like clays on drying. According to some authors (e.g. Lal, 1979b, ISSS Working Group RB, 1998b) these soils have a small available water capacity. Others (e.g. Wolf, 1975; Resende et al., 1996a,b) stress the importance of other factors than water retention that co-determine water availability, such as rooting depth as conditioned by soil chemical barriers, soil fertility and crop type. Van den Berg et al. (1997) conducted a literature review on soil water characteristics of strongly weathered soils world-wide, and found inconclusive results (see also Chapter 6). Their multiple regression analyses of data on volumetric core samples suggest that available water capacity (*AWC*) of these soils is related to clay content, bulk density and specific surface, but only 48 % of total *AWC* variance could be explained by these variables. Regression with particle size distribution alone revealed a positive correlation coefficient with clay content, explaining only 21 % of variance.

2.4.2 Chemical properties

Strongly weathered soils are chemically poor. Organic carbon content of the topsoil is small, typically between 5 and 20 $g\,kg^{-1}$. Insufficient P availability is a major constraint, because phosphates are inactivated on positively charged surfaces of iron compounds and kaolinite (Lathwell, 1979). Other nutrients have leached out because of long continued downward water percolation and the low cation exchange capacity (CEC). This has resulted in acidity and consequent occupation of the cation exchange complex by aluminium (Kamprath, 1977). Related problems include Al toxicity, H^+ toxicity, inhibition in uptake of Mg, Ca and K and inhibition in root growth (Marschner, 1991). These problems can be solved partially by lime amendments and application of fertilizers. Toxic Al levels below the plough layer are difficult to adjust by liming and may form a chemical barrier to root penetration (Furlani et al., 1991, Foy, 1992). This can be relieved by large surface applications of more soluble gypsum (Reeve & Sumner, 1972, Sousa & Ritchey, 1986), which however is considered too costly for most farmers. Additional research is necessary to develop means to accurately diagnose soil/climate/crop combinations where yield increases will adequately repay application costs (Ritchey & Sousa, 1997). (Summary) crop growth models could possibly play an important part in this. The level at which soil acidity restricts root growth depends on plant species and genotype, soil type and horizon, parent material, concentration and species of Al, soil structure and aeration and climatic conditions (Marschner, 1991). The processes involved are only partly understood. Soil scientists often use percentage Al saturation (percentage of effective cation exchange capacity (ECEC) occupied by Al^{3+}; Kamprath, 1977) as a rule of thumb to distinguish strongly weathered soils in which root penetration is likely to be inhibited. Levels of 50-60% Al saturation are considered critical to the roots of many crops (Foy, 1992). The soil classification system in use in Brazil labels soils with the adjective allic when Al saturation of the B horizon exceeds 50 %. The WRB uses the adjective alumic for the same purpose but Al saturation seems to be determined in relation to the CEC rather than to the ECEC (Spaargaren, personal communication 2000).

2.4.3 Suitability for agriculture

Lessons from the past suggest that agriculture with low external input levels can only be sustainable on strongly weathered soils if land use is very extensive. Examples are shifting cultivation with long fallow periods, selective extraction of wood, fruit and latex or very extensive grazing (Sanchez, 1981, 1997, Demattê, 1988, ISSS Working Group RB, 1998b). Increasing land use intensity without increasing input of plant nutrients leads inevitably to a downward spiral of fertility depletion, lower yields, smaller amounts of manure and crop residues, less plant cover and increased runoff and erosion. Obviously, strongly weathered soils are more prone to fertility depletion than soils with high activity clays and nutrient reserves incorporated in primary minerals.

However, most strongly weathered soils are suitable for carefully managed high-input agriculture. High yields can be obtained if soil acidity and nutrient deficiency are remedied. Extremely poor Geric Ferralsols have been reported to produce on-farm maize yields of 16 $ton\,ha^{-1}$ in South East Brazil (Bernardes, 1988). Careful management is required because the good workability of strongly weathered soils tempts farmers to use heavy machinery on too wet soils. This causes the formation of compacted plough pans, with serious consequences for rootability, water infiltration capacity and erosion (Klamt et al., 1983). Direct drilling, terracing and green manuring have been reported to prevent such problems, and can even improve degraded soils (Debarba & Amado, 1997; Hernani et al., 1997).

Different land use potential ratings are attributed to different kinds of strongly weathered soils. In Brazil, dusky red soils are considered more productive than yellow red ones and clays are considered "better" than sandy loams (e.g. Demattê, 1988; Oliveira et al., 1992, Oliveira & Van den Berg, 1985). Inferior qualities of yellowish and sandy soils are mainly blamed on soil fertility and water availability aspects, but this is not always reflected by analytical data.

2.4.4 Spatial variability

Several geo-statistical studies have been conducted on spatial variability of strongly weathered soils (a review is given in Chapter 4), mostly at short spatial scales (<1 to 100 m). Results suggest that soil characteristics that are easily modified (e.g. pH, base saturation, P content) can vary considerably at short range, even in apparently homogeneous areas. Soil characteristics that are more stable in time (e.g. soil texture, organic matter content, CEC) also seem to be more homogeneous in space. Implications for soil mapping have not been systematically studied and it is not clear if there are similar patterns of spatial variability in similar strongly weathered soils in different regions.

2.5 Research topics

Much is known about strongly weathered soils in general terms of their formation, distribution, chemical and physical conditions. It has been proven that it is possible to establish sustainable, highly productive land use systems on several types of strongly weathered soils, but there are still many knowledge gaps. More systematic and integrated research is necessary to fill these gaps. Poor correspondence between classification systems reflects some lack of understanding and also a somewhat equivocal objective of soil classification, namely to create soil groupings that are homogeneous with respect to their genesis as well as to management properties. Frequent modifications in terminology and changes of definitions reflect the increasing concern of soil taxonomists with management properties, but also contributes to confusion among non-specialists. This may lead to failure of another important objective of soil classification, which is to improve communication on soils.

The following questions are addressed in the subsequent chapters:

- How do strongly weathered soils vary within apparently homogeneous soilscapes, what are the causes of spatial variation, and is it possible to identify characteristic patterns in how these soils vary in space?

- How well are soil classification units and soil mapping units correlated with relevant management properties of strongly weathered soils?

- Is it possible to identify consistent relations between soil water retention characteristics and other physical and chemical soil properties?

- What are the prospects for using summary crop growth models to evaluate land use management alternatives, e.g. to diagnose soil/climate/crop combinations where yield increases will adequately repay application costs of soil amendments?

- How important are restrictive physical and chemical soil characteristics in relation to soil water availability?

3. THE STUDY AREAS

3.1 Araras

3.1.1 Location

The Araras study region is located in the state of São Paulo, in South-East Brazil (figure 3.1). It is sited at 22°15' S and 47°20' WG at approximately 675 m above mean sea level. Figure 3.2 gives the locations of study fields in the region. All fields belong to the Usina São João sugarcane enterprise.

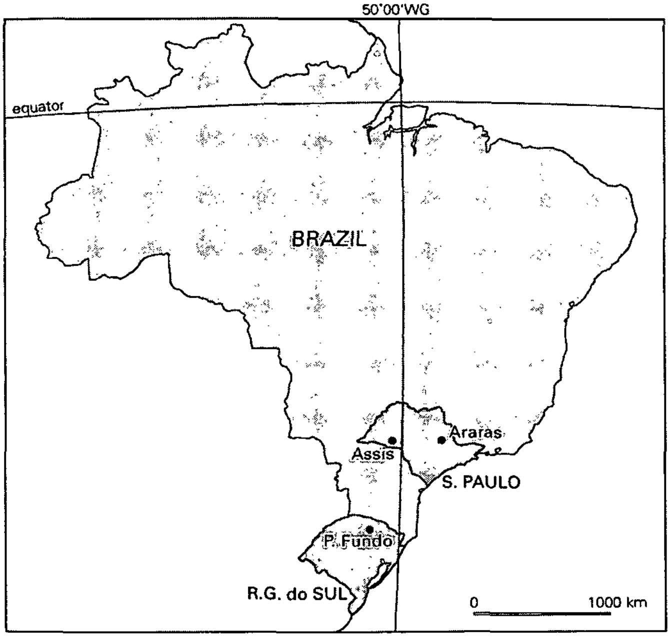


Figure 3.1 Location of the study regions Araras (SP), Assis (SP) and Passo Fundo (RS)

3.1.2 Climate

Climate is subtropical humid, with humid hot summers and relatively dry winters. Köppen classification is Cfa, transitional to Cwa. Frosts are rare. Table 3.1 presents monthly average climate data of Limeira. The water budget, calculated according to Thornthwaite & Mather (1955), suggests moisture deficiency between May and September. The soil moisture regime according to Soil Survey Staff (1975) is udic and the soil temperature regime is hyperthermic (Oliveira et al., 1975).

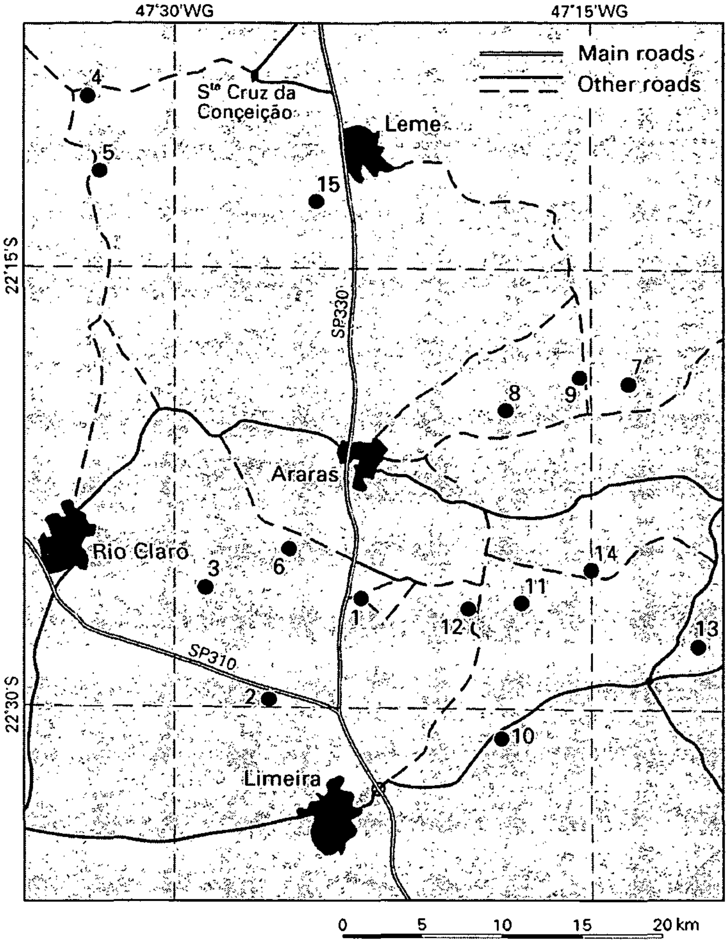


Figure 3.2 Location of study fields in the Araras region

3.1.3 Geology

The Araras region has a complex geological structure (IPT, 1981). The two major lithologies are (1) sedimentary rocks (conglomerates, sandstones, argilites and siltites), of marine and fluvial origin, and Pleistocene to carboniferous age; and (2) igneous basic rocks, mainly intrusive laccoliths and stocks, locally basalts, of the Mesozoic Serra Geral formation. Highway SP330 (figure 3.2) roughly follows the boundary between these major lithologies. Sedimentary rocks occur predominantly west of the highway.

Table 3.1 Average monthly climate data at Limeira (22°32' S, 47°27' WG; 639 m a.m.s.l., 1940-1990)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average mean t, °C	22.8	22.7	22.2	20.4	18.3	17.0	16.8	18.7	20.0	20.9	21.5	22.0
Average max. t, °C	29.1	29.2	28.9	27.5	25.3	24.4	24.7	27.2	27.7	28.2	28.5	28.5
Average min. t, °C	18.0	18.1	17.2	14.8	12.4	11.1	10.6	12.0	13.3	14.9	15.9	17.0
Precipitation, mm	236	192	165	68	56	41	28	31	63	128	153	231
n° of rainy days	18	16	14	7	6	5	4	3	6	11	12	17
Bright sunshine, hours	194	181	214	213	208	195	219	226	202	208	212	178
Relative humidity, %	80	81	80	77	75	74	70	64	66	72	75	78
Wind speed, m s^{-1}	1.8	1.6	1.5	1.5	1.5	1.5	1.5	1.8	1.9	2.0	2.0	2.0

Source: Instituto Agronômico de Campinas

3.1.4 Physiography

The region is characterised by extensive (several km^2) gently undulating plateaux, traversed by valleys with long (1 000-2 500 m), almost linear slopes, generally between 5 and 10%. A few inselbergs with very steep slopes (unto >100%) in the north-western part of the region (just south of study field 4 in figure 3.2) indicate a transition to the Serra de São Pedro mountains.

3.1.5 Soils

Oliveira et al., (1977, 1981) report that strongly weathered soils are dominant in the region. There is a clear correlation between soil type and parent material. Dusky Red Latosols, and Dusky Red Earths with a very fine clayey texture are associated with basic igneous rocks. Red Yellow Latosols, Red Yellow Podsolics and Quartzose Sands originate from sedimentary rocks. Dark Red Latosols are typical on reworked materials that originate from nearby igneous and sedimentary rocks.

Dark Red and Dusky Red soils may be rich in bases (eutrophic) or poor (dystrophic), but rarely contain more than 50% aluminium on the exchange complex (allic). Most Red Yellow soils are allic. Soils with a textural B horizon are common on slopes steeper than 10%.

3.1.6 Natural vegetation

Only traces of the original vegetation are left in the region. The clayey Dusky Red and Dark Red soils were once covered with subtropical evergreen seasonal forest. The medium-textured and sandy soils were under cerradão and cerrado (Oliveira et al., 1982).

3.1.7 Agriculture

An assessment of land suitability for agriculture in the Araras region (Oliveira & Van den Berg, 1983, 1985) indicated almost 70% of the land surface area as regularly or well suited for capital intensive annual cropping and well suited for pasture, forestry and long cycle crops. The major limitations mentioned for crop production are nutrient availability and soil acidity. Large applications of lime and fertilizers are required to obtain good yields.

Sugarcane is the principal crop in the region. The Usina São João sugar- and alcohol- plant is the largest landowner, with 30 000 ha of sugarcane fields. The second major commodity is citrus, mainly on medium-sized (100 - 1 000 ha) enterprises. Sandy soils in the north-western part of the region are replanted mainly to pinus and eucalyptus, but some are planted to sugarcane (e.g. figure 3.2, fields 4 and 5). Coffee, black bean, soybean, maize and vegetables are less widely grown and confined to small (< 100 ha) and medium enterprises.

Farming enterprises in the area use modern management; they base fertilisation and liming on soil analyses, use quality seed and plant material, construct broad-based contour terraces on sloping lands, control pests and diseases timely and according to recommendations and mechanise soil tillage and seeding. Irrigation is applied in several citrus orchards and on some (smaller) farms that produce vegetables or beans during winter. The sugarcane estate has an extensive irrigation network that is mainly used for the distribution of vinasse, a by-product of the alcohol plant, with a high content of nitrogen, sulphur and, especially, potassium. Fertirrigation with vinasse is primarily used to supply nutrients; not water. Sugarcane and citrus are harvested manually. According to local farmers, the average yield on well-managed enterprises is approximately 75 000 kg ha^{-1} per 12 months of fresh sugarcane stalks (growing periods of sugarcane vary between 14-20 months for plant cane and 10-16 months for rattoon cane); or 40 000 kg ha^{-1} yr^{-1} of fresh orange or lemon fruits.

3.2 Assis

3.2.1 Location

The Assis study region is in the west of São Paulo state (figure 3.1); the town of Assis is located at 22°40' S and 50°25' WG, at an elevation of approximately 550 m above mean sea level. Figure 3.3 shows the location of study fields in the region. The sugarcane fields (1-11) belong to two large, related, sugar and alcohol plants. Fields 4 and 9 to Usina Capivara, and the others to Companhia Agrícola Nova América. The soybean/wheat fields (21-28) belong to different medium sized farms, which co-operate technically and commercially through the Cooperativa Agrícola de Pedrinhas Paulista.

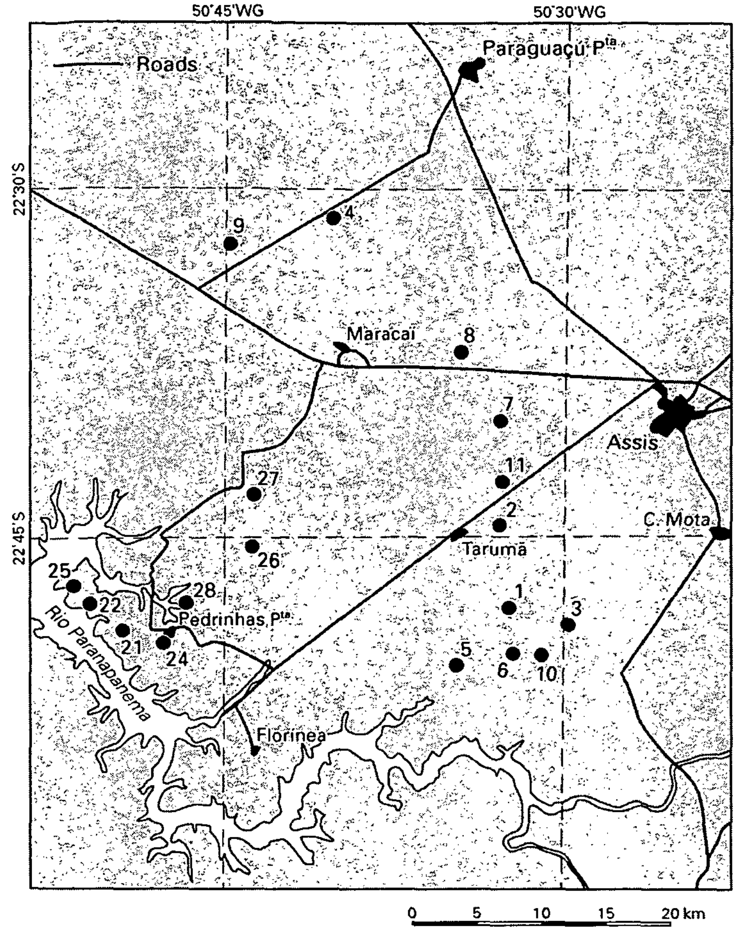


Figure 3.3 Location of study fields in Assis region. 1- 11: sugarcane fields; 21-28: soybean/wheat fields

3.2.2 Climate

Climate is subtropical humid, with moist and hot summers and relatively dry winters. Köppen classification is Cfa, transitional to Aw. Frosts are rare. Table 3.2 summarises characteristic data. Average temperature is considerably higher than in the Araras region, especially in summer. Annual precipitation is similar, but rainfall is more regularly distributed than in Araras. In the Assis region it is feasible to grow a crop during the cool season without irrigation. Soil moisture regime is udic; soil temperature regime is hyperthermic (Oliveira et al., 1975).

Table 3.2 Average monthly climate data of C.A.N.A., Assis, (22°48' S, 50°32' WG., 400 m a.m.s.l.)[1)]

	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average mean t °C[2)]	25.2	25.9	25.2	22.6	20.1	17.8	18.3	20.3	21.1	23.2	24.5	25.0
Average max. t, °C[2)]	31.1	31.6	31.6	29.5	26.6	24.7	25.5	28.1	28.1	30.3	30.5	30.9
Average min. t, °C[2)]	19.4	20.2	18.9	16.3	13.6	11.0	11.2	12.5	14.1	16.2	17.9	19.2
Av.Soil t, °C[3)], at 30 cm	27.7	28.4	29.1	27.7	22.4	19.6	18.8	20.8	24.0	25.3	27.3	29.4
Prec. mm[4)]	186	152	125	87	90	76	45	44	88	139	134	197
n° rain days[5)]	12	12	10	7	7	6	3	4	6	8	9	14
Sunshine h.[6)]	210	179	219	222	211	207	226	230	188	212	216	181
Relative humidity, % [7)]	78	81	78	77	79	76	68	65	67	66	69	76
Wind speed, m s^{-1} [7)]	1.4	1.3	1.2	1.4	1.3	1.5	2.1	2.2	2.6	2.3	2.4	1.8

[1)]Hours of sunshine at Cambará (23°00S, 50°02'WG., 450 m a.m.s.l.);

[2)]1975-jul/'89; [3)]jun/'88-jul/'89; [4)]1949-1988; [5)]1980-1989; [6)]26 yrs between 1957 and 1990; [7)]1982-jul/'89.

Source: Instituto Agronômico de Campinas

3.2.3 Geology

Two formations dominate the geology of the region (IPT, 1981). (1) The Mesozoic Serra Geral formation consists of basalts with arenitic intercalations and occurs in the south of the study region. (2) The Adamantina formation is also of Mesozoic origin and consists of sandstones and laminated rocks of varying texture. It occurs in the north of the Assis region. Some of these sedimentary formations are cemented by lime. The border between the two formations follows approximately the line Assis-Maracaí (figure 3.3). Pleistocene terraces of the Paranapanema river cover a minor part of the region and are not indicated on the map of IPT (1981). They consist of sandy and loamy unconsolidated sediments.

3.2.4 Physiography

The physiography of the region is similar to that of the Araras region. Extensive (several km^2), gently undulating plateaux are traversed by valleys with long (1 000-2 500 m), almost linear slopes, normally between 5 and 10%.

3.2.5 Soils

Most common soils of the region are dark red, well drained, strongly weathered soils with low activity clays. Soils with a true textural B horizon are confined to slopes steeper than 10%. The transition from the A horizon to the B horizon is gradual and the difference in clay content between A and B horizons is less than 15%.

Sandy and medium-textured Dark Red Latosols, Dark Red Podsolics and Red Yellow Latosols form in sedimentary deposits. Very fine clayey Dusky Red Latosols and Dusky Red Earths form on weathering from basalt. Dark Red Latosols with clayey texture are believed to have formed in reworked materials.

Most sandy and medium-textured soils have a poor base status, high aluminium saturation and very low clay activity (some have an ECEC<1.5 $cmol_c\,kg^{-1}$ clay). Exceptions are relatively young eutrophic Podsolic soils on sedimentary rocks with lime cementation. Soils with a clayey texture can be eutrophic, dystrophic or allic (Bognola et al., 1996). A statistical study by Jansen (1991) supports to the hypothesis that soils on stable plateaux tend to be more acid (higher Al, lower base saturation) than soils on slopes, because the former are subject to more intensive leaching and less erosion.

3.2.6 Natural vegetation

Natural vegetation is practically extinct in the region. The clayey Dusky Red and Dark Red soils of the Assis region are associated with subtropical evergreen seasonal forest; the medium-textured and sandy soils had a *cerradão* or *cerrado* vegetation.

3.2.7 Agriculture

Agriculture in the region can be split in two categories: (1) Large enterprises, mainly with sugarcane, with thousands of hectares of land and hundreds to thousands of employees, including agricultural engineers and technicians. (2) Medium sized farms (40-200 ha) that usually produce soybean in the warm, rainy season (October to March) and wheat in the cool, relatively dry season (April-September). These farms rely mainly on family labour although most have one or two employees.

Both types of enterprise use advanced management methods. Irrigation is applied on few soybean/wheat enterprises only. Combine harvesters are used for soybean and wheat.

Sugarcane management in the Assis region is similar to that in the Araras region. Average yields in the region amount to some 2 500 $kg\,ha^{-1}$ soybean; 3 000 $kg\,ha^{-1}$ wheat and 75 000 $kg\,ha^{-1}$ fresh sugarcane stalks per 12 months.

3.3 Passo Fundo

3.3.1 Location

The Passo Fundo region is located in the State of Rio Grande do Sul in Southern Brazil (figure 3.1). Passo Fundo is sited at 28°15'S, 25°30'WG, at an elevation of approximately 680 m above mean sea level. Figure 3.4 shows the location of study fields in the region. Field 7 belongs to the Brazilian Agricultural Research Enterprise,

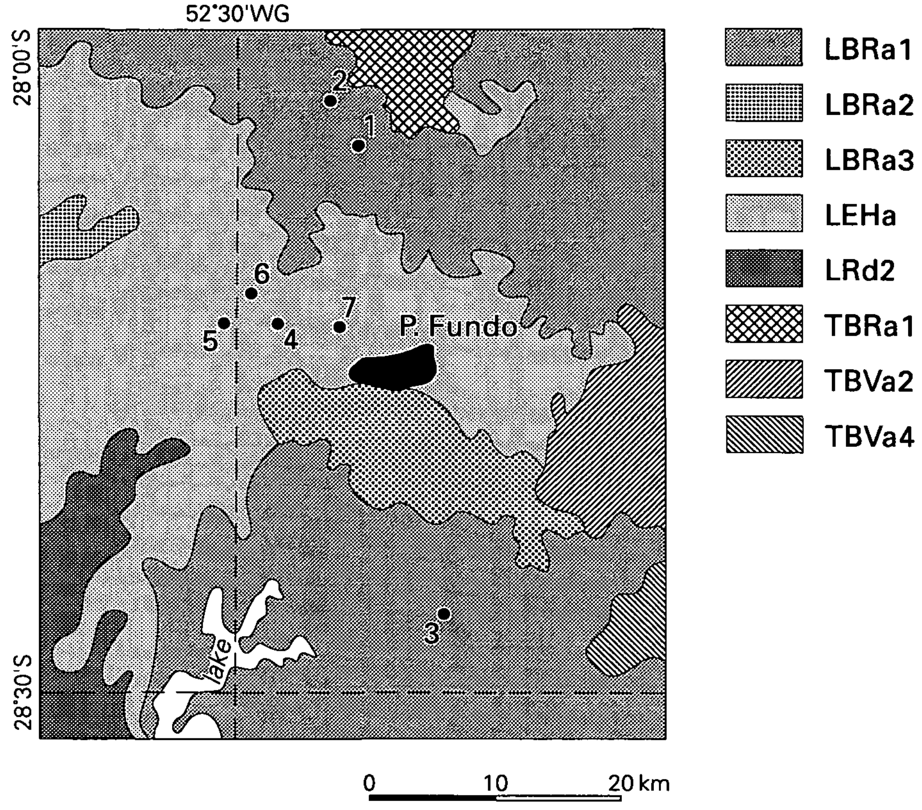


Figure 3.4 Location of study fields and soil distribution in the Passo Fundo region
Legend: see table 3.4.. Source: IBGE/EMBRAPA, 1986.

EMBRAPA. The others belong to four large commercial enterprises: fields 1 and 2: Fazenda Butiã, field 3: Fazenda Bruno Augustin, field 4 and 6: Fazenda Grazziotin and field 5: Granja São José.

3.3.2 Climate

Climate is subtropical humid, transitional to temperate, with a Köppen classification of Cfa, transitional to Cfb. Table 3.3 presents some average monthly data. There is no dry season but the rainfall pattern is far from regular and the annual precipitation sum fluctuates considerably. Dry spells of several weeks are common. Frosts occur from May to September; sometimes even in November. This limits the choice of crops in the region. Another problem is the occurrence of heavy rain showers ($\pm$ once in a year >100 mm day^{-1}) that enhance erosion and cause trafficability problems and inundations. The soil temperature regime (Soil Survey Staff, 1998) is thermic. The most common soil moisture regime is probably udic, possibly perudic.

Table 3.3 Average monthly climate data of Passo Fundo (28°15' S, 52°24' WG, 684 m a.m.s.l)

	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average mean t, °C[1)]	22.2	21.9	20.6	17.0	14.6	12.9	12.8	13.8	15.5	17.4	19.3	21.2
Average max. t, °C[1)]	28.4	27.9	26.4	23.1	20.5	18.2	19.2	19.8	21.5	23.7	25.9	27.8
Average min. t, °C[1)]	17.5	17.3	16.1	12.9	10.6	9.1	9.0	9.7	11.3	12.9	14.4	16.1
Av.Soil t °C[2)] (at 50cm)	24.3	24.4	23.6	20.7	17.7	14.7	14.0	14.6	15.7	18.4	20.9	23.1
n° days with frosts[3)]	0	0	0	3/10	3	4	3	2	1	2/10	1/10	0
Precipitation mm[1)]	155	150	130	120	100	138	134	173	197	183	119	164
n° rainy days[1)]	11	10	9	7	8	8	9	10	11	10	9	10
Bright sunshine, hours[1)]	230	211	211	194	183	154	172	169	154	202	230	257
Relative humidity, %[1)]	70	72	73	74	74	77	74	72	72	71	66	66
Wind speed m s^{-1} [1)]	4.0	3.8	4.0	4.1	4.1	4.1	4.3	4.7	4.7	4.2	4.6	4.2

[1)] 1960-1989; [2)] 1975-1990; [3)] Defined as n° of days with minimum temperature at a grass surface <0°C.

Source: EMBRAPA/CNPt

3.3.3 Geology

The principal geologic formations of the region are the Serra Geral and the Tupanciretã (IBGE, 1986). The Serra Geral formation dates from the upper Jurassic and lower Cretaceous. It consists mainly of basalts that have less Fe and Ti compounds than the basalts and intrusive rocks of the same formation in the Araras and Assis regions. The Tupanciretã formation in the study region consists of fluvial sandstone, generally cemented by iron oxides. It occurs predominantly on the higher parts of the topography. It is difficult to distinguish these sandstones from those of the Botucatú formation (of aeolic origin) that occur as intertraps in the basalts. The Tupanciretã formation probably dates from Palaeocene or upper Cretaceous.

3.3.4 Physiography

Relief is rolling to hilly. It is made up of a concatenation of small hills with rounded tops and convex slopes, locally called *cochilhas* (from cocha = hip). The slopes are rarely steeper than 20%; slope lengths are from about 400 m to 1 000 m. Oval depressions, with amphitheatric rims and hydromorphic soils at the bottom, are exclusive to areas with sandstones. Erosion is quite conspicuous (cut-in roads, gullies) in sandstone areas and less so in areas with basalt.

Table 3.4 Summary of soil mapping units in the Passo Fundo region

Code/Name mapping unit	**LBRa**
Dominant soil class	Brown Latosol, intergrade with Dusky Red Latosol, allic
Texture	clay content > 600 g kg^{-1} throughout
Colour of B horizon	Reddish, Hue 2.5YR to 4YR
Fe_2O_3 content	> 180 g kg^{-1}
Parent material	Basalt
Remarks	LBRa1 contains no specified impurities. LBRa2 and LBRa3 are associations with respectively Dark Red Latosols and Structured Brown Earth.
Code/name mapping unit	**TBRa1**
Dominant soil class	Structured Brown Earth, intergrade with Structured Dusky Red Earth, allic, clayey
Texture	clay content > 600 g kg^{-1} throughout
Colour of B horizon	Reddish, Hue 2.5YR to 4YR
Fe_2O_3 content	> 150 g kg^{-1}
Parent material	Basalt
Discr. Criteria II x I	Presence of a textural B horizon with shiny ped surfaces
Code/name mapping unit	**LEHa**
Dominant Soil Class	Dark Red Humic Latosol, allic, clayey
Texture	clayey in the B horizon
Colour of B horizon	Reddish, Hue=2.5YR
Fe_2O_3 content	80 - 180 g kg^{-1}
Organic C content	> 10 g kg^{-1} at 1 m depth
Parent material	Sandstone with admixtures of weathered basalt
Discr. criteria III x I	Washed out quartz grains throughout the profile; smaller Fe_2O_3 content
Discr. criteria III x II	III has Latosolic B horizon
Others	**TBVa2**: Intergrade of Structured Brown Earth with Dark Red Podsolics. **TBVa4**: As TBVA2 + Soils with high activity clays.

Source: IBGE/EMBRAPA, 1986

3.3.5 Soils

Two exploratory soil surveys have been carried out in the Passo Fundo region: (1) Ministério da Agricultura (1970,1973) produced a soil map at scale 1:750 000; and (2) IBGE/EMBRAPA (1986) made a soil map at a scale of 1:1 000 000. The second map is based on radar images and shows more detail. Figure 3.4 presents the part of that map covering the study region. The legend is given in table 3.4. Most soils in the region are well drained and marked by low activity clays. The colour of the A-horizon is typically 5YR 3/3, and that of the B-horizon (at 2 m depth) 2.5YR 3/6. Colour requirements of a prominent A-horizon are rarely met. B-horizons commonly show evidence of clay illuviation. Clay increase and/or the presence of shiny ped faces are often too weak to meet the requirements of a textural B horizon (see table 2.4). These requirements were much less restrictive in the 1970's, when the map of the Ministério da Agricultura (1970,1973) was published. This explains that more soils with a textural B-horizon occur on that map.

Loamy topsoils are associated with sandstone parent materials whereas soils formed on basalt are clayey throughout. Most soils formed in eroded and reworked materials, so that a wide variation of textures can be found.

All virgin upland soils in the region have a low base status and high aluminium saturation. They are allic. Since the 1960's, when most of these soils were reclaimed for agriculture, liming has been applied, causing increased base saturation percentage and decreased Al saturation of upper soil layers.

3.3.6 Natural vegetation

The climax vegetation is *campo grosso*: poor grassland with *Paspalum notatum* and *Aristida pallens* as dominant species. Forests were common, as small "islands" in the campos, and in strips along rivers. Some of the most typical species in these forests are the Brazilian pine: *Araucaria angustifolia* and the mate tree: *Ilex paraguaniensis.*

3.3.7 Agriculture

Before the introduction of lime and fertilizers, soils of the region were considered "Not Suitable" for cropping. The *campos* were used for extensive grazing and burnt for rejuvenation each year, at the end of winter. Today, three farm types occur in the region: (1) Large enterprises, with more than thousand hectares of land and more than ten employees, among whom agricultural engineers and technicians; (2) medium-sized farms (40-200 ha) that rely on family labour and one or two employees; and (3) small farms, mostly with 10 ha or less, and exclusively run with family labour.

The first two types produce soybean in the warm season (November to May) and wheat, oats or barley in the cool season (June to November). It is not uncommon to sow pasture of grass, oats and/or clover just after the summer harvest. Permanent pastures are common on steeper slopes with medium-textured soils. Average yields of well-managed farms in the region are approximately 2 500 kg ha^{-1} soybean and 3 000 kg ha^{-1} wheat.

The main difference in management between the first and the second farm type is the more efficient application of know-how by large enterprises that produce soybean and wheat for seed, whereas the medium farms produce for the industry. Few farmers use irrigation. Small farms produce maize, melons, milk, poultry, beans and vegetables, both for subsistence and for the local market. They use animal traction and manpower, and do apply lime, fertilisers and pesticides, but generally without prescription.

PART II

VARIABILITY OF APPARENTLY HOMOGENEOUS SOILSCAPES

4. SPATIAL ANALYSIS

4.1 Introduction

Unresolved spatial soil variability is one of the major factors that limit the quality of soil inventories, and evaluations based hereon. Therefore, spatial variation of soils should be quantified. Results of spatial analysis can be used to optimise sampling schemes for soil surveys and to quantify the impact of errors/uncertainties, originating from unresolved variability, on calculated estimates of e.g. land-use system productivity, soil erodibility, fertiliser requirements and so on.

Statistical methods to quantify spatial variability of soils have been proposed since the 1920's (Waynick, 1918; Harris, 1920). Such methods are usually referred to as geostatistics. The most important ones are nested analysis of variance and semivariance analysis (Webster, 1985; Webster & Oliver, 1990).

Nested analysis of variance describes the distribution of variance over exponentially increasing spatial scales. It is carried out on data collected in nested sampling schemes, i.e. samples distributed hierarchically in space This technique is especially suited for a rough assessment of predominant scales of spatial variability (e.g. Nortcliff, 1978; Burrough & Kool, 1981, Corsten & Stein 1991).

The semivariance, $\gamma(h)$, describes the variance of differences between sites as a function of their spatial separation h (called lag) and is usually estimated from data collected from sampling grids or along transects over linearly increasing values of h (Burgess & Webster, 1980). Semivariance analysis is best suited for refined assessment of spatial variability once rough estimates are available. Hence nested analysis of variance and semivariance analysis are complementary techniques (Oliver & Webster, 1986, 1987).

So-called classical statistics can also be useful for examining spatial differences. The analysis of variance within and between management units helps to assess whether soils within a management unit can be treated alike and to interpret yield records in terms of agricultural potential.

Relatively little information is available on the spatial variability of strongly weathered soils. Harradine (1949) argued – without presenting conclusive data - that soils in an advanced stage of profile development would show less spatial variability than more recent soils. Oliveira (1972), presented results that suggest that this is untrue for many soil characteristics. His regular sampling (50x50 m grid) of an apparently homogeneous area of 16.5 ha, revealed a complex pattern comprising 2 soil orders, 4 great groups, 13 families and 17 series, as classified according to a preliminary version of the USDA Soil Taxonomy. Other studies that used classical statistics are the ones conducted by Oliveira & Rotta (1973), Oliveira (1975) and Cadima et al., (1980), all in São Paulo State. Soil survey reports of the Instituto Agronômico de Campinas (e.g. Oliveira et al., 1982) include tables on the variation of major soil characteristics within each mapping unit. Converging evidence from these studies suggest that, in general, chemical soil characteristics such as base saturation and sum of exchangeable bases present considerable variation within mapping units, whereas the mapping units are more homogeneous with respect to soil texture, CEC and soil organic matter content. The latter variables present major variation between mapping units, at large spatial scales, say > 1 km. Apparently, the different spatial levels of soil variability for different characteristics reflect different soil forming factors; e.g. management for chemical soil characteristics at very short distances and parent material for soil texture at long distance. However, the possibility of some bias in these results may not be excluded, because the statistical analyses were done on the same observations that had been used to delineate the mapping units.

Published geostatistical studies on strongly weathered soils have been done mostly at a detailed level, with distances between observations from less than 1 m up to little more than 100 m. In general, these studies suggest that considerable variability occurs within 5 to 15 m distance. For example, Bacchi (cited by Reichardt et al., 1986) analysed pH data on samples of a Dark Red Latosol under sugarcane near Araras (SP), with 1 m sampling intervals along a transect of 50 m length. Significant autocorrelation (at 5 % level) was found up to 5 m distance. The standard deviation was 0.35 with extreme values of 4.6 and 6.3. Libardi et al. (1986) analysed the spatial variability of a Dusky Red Earth in Piracicaba (SP) with respect to soil water content, soil texture and particle density along a 150 m transect with a sampling distance of 0.5 m. All studied variables, except silt content, showed spatial dependence up to some 15 m; spatial dependence was shown up to 40 m for silt content. Interestingly, the semivariograms were considerably differently shaped, e.g. suggesting cyclic variation for particle density. Standard deviations for particle size fractions were rather small, e.g. 40 $g\,kg^{-1}$ for clay content. A study by Silva et al., (1989) on the variability of depth and thickness of a compact layer in the same area, along a transect of 40 m, with observations each 10 cm, revealed spatial dependence up to less than 2 m. Cyclic variations were, in this case, attributed to soil management (c.f. Burrough et al., 1985; McBratney & Webster, 1981).

For semi-detailed and reconnaissance soil surveys it is necessary to quantify spatial variability at larger scales, up to several kilometres. This is an expensive and laborious job (Isaaks & Srivastava, 1989; Burrough, 1993). One method to reduce costs is to determine variables that are difficult or expensive to measure with a low observation density and correlated easily measured ones at high density (e.g. Burrough, 1991). A possible alternative procedure is based on the hypothesis that the spatial variations of similar soils of different regions may be analogous. If spatial variability proves to be similar in landscapes dominated by soils of the same taxonomic groupings at a high level of generalisation, then optimised sampling strategies determined for a limited number of representative areas may be useful for optimising sampling in new areas. Additionally, quantified knowledge on spatial variability would contribute to a better understanding of relations between spatially variable soil (forming) processes and soil characteristics, feeding even more the development of improved survey methods. This would be of great importance in the case of strongly weathered soils in Brazil. Most of the regions where they dominate have only been mapped at exploratory-reconnaissance scale (e.g. 1 : 0.5M to 1 : 1M), with a very low density of ground observations.

The objectives of this study are: (1) to determine the spatial variation of some properties of strongly weathered soils under sugarcane and soybean/wheat rotation in three regions in Southeast and South Brazil and assess possible similarities between these regions; and (2) to assess to which extent land-use (sugarcane vs. soybean/wheat) may influence soil properties and their spatial variability.

4.2 Materials and methods

The selected study regions are situated near Araras (SP), Assis (SP) and Passo Fundo (RS), as indicated by figures 3.1, 3.2, 3.3 and 3.4. These regions are characterised by the abundance of strongly weathered soils: mostly Latosols, some Dusky Red and Brown Earths, Podzolics Tb and Quartzose Sands, according to the soil classification system in use in Brazil (Camargo et al., 1987).

The following research strategy was adopted:

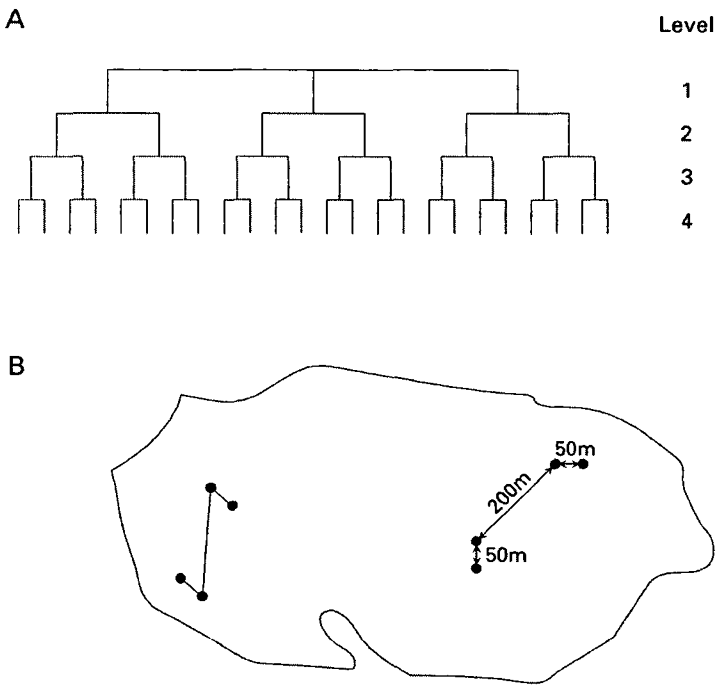
i. A total of 42 fields (on-farm management units) was selected in the three regions, on the following criteria:
   - The fields should not have evident (previously mapped or visually observable) soil boundaries within them;
   - They cover, together, most variability of strongly weathered soils in each region;
   - They belong to well-managed enterprises;
   - In the Araras region all selected fields have sugarcane;
   - In the Assis region, fields have either sugarcane or soybean/wheat rotation.
   - In the Passo Fundo region all selected fields have soybean in summer and wheat (or other cereals) in winter;

   Selection of fields was based on available soil maps, complemented by indications of local farmers and extension officers. The following soil maps were used: Araras region: Oliveira et al (1977), Oliveira et al. (1981) and Prado et al. (1981), all at scale 1 : 100 000; Assis region (only for sugarcane fields): Souza Dias (1985), scale 1 : 50 000; Passo Fundo region: IBGE/EMBRAPA (1986), scale 1 : 1 000 000 and Ministério da Agricultura (1970, 1973), scale 1 : 750 000.
ii. A nested auger sampling and nested analysis of variance were done on part of the fields to get a rough idea of soil variability at different spatial scales;
iii. an overall, more or less regular, auger sampling was used as a base for semivariance analysis and analysis of variance by field to get a more refined idea of spatial soil variability in the range from 0.3 to 1.0 km, and to compare soil properties between different land use systems and regions.

4.2.1 Nested sampling

For the nested sampling, 7 fields were selected in Araras, 4 in Assis and 7 in Passo Fundo.

In the regions of Araras and Passo Fundo, sampling was done at four levels. The fields formed the highest level. Distances between the 7 selected fields varied between 3 and 30 km. For the second level two points were arbitrarily chosen in each field, with the condition of a minimum distance of 500 m between them (the average distance between the points was approximately 600 m). From each point two other sampling levels were derived with random direction and medium distances of 200 m (third level) and 50 m (fourth level) respectively; so that a total of 7x2x2x2=56 sampling points were analysed in each region. The sampling design is schematically shown in figure 4.1.



Level	Number of replicates	Spacing (m)
1	7	>3000
2	2	600
3	2	200
4	2	50

Figure 4.1 Lay-out of the nested sampling schemes in Araras and Passo Fundo.
A. Hierarchy of sampling levels
B. Example of spatial distribution of sampling sites in one field.

A slightly different sampling scheme was used in the Assis region. The number of spatial levels in that region was 5, with 4 fields and 2, 2, 2 and 3 repetitions at distances of 750 m, 350 m, 125 m and 30 m respectively, so that a total of 4x2x2x2x3=96 sites were sampled.

At each sampling site, soil samples were collected from two depths: 0-20 cm and 60-80 cm. These were analysed for colour, clay content and pH. Representative values for penetrometer resistance were obtained in the Araras and Assis regions, by taking the number of strokes on a penetrometer of impact to penetrate the layers of 0 to 30 cm and 30 to 65 cm in the Araras region, and the layer of 20-40 cm in the Assis region. At each site, 6 replicates were taken within a square of about 1.5x1.5 m. Penetrometer data were standardised to zero mean and unit variance within fields to "neutralise" the effect of rain showers during the period of field work. Cumulative variance at the 600 m level was considered as 100%. Hence analysis of spatial variation of penetrometer data is not possible between fields in Araras and Assis. Penetration resistances in the Passo Fundo region were determined at the sampling sites of only 5 fields (due to unfavourable weather conditions) and 2 lower levels of sampling were introduced: the first with 2 replicates, at a distance of 1.5 m, and a second with 3 replicates with about 0.2 m distance between observation points. Readings were done at 15, 30 and 45 cm depth with a penetrographer. The results of the 0.2 m level sampling were averaged prior to the analysis of variance. These data were not standardised, because observations in the five fields were done within a few days, without rain.

Soil colour was determined on moist samples in the field by using the Munsell Soil Colour Charts (Munsell, 1975). Colour hues were transformed to numerical values according to the method used at the Instituto Agronômico de Campinas (Lepsch et al, 1978): 7.5R = 10, 10R = 20, 2.5YR = 30, 5YR = 40 etc. It is felt that this transformation from the original circular Munsell scale to a linear scale is justified because the colours of all samples studied occur in the red-yellow segment (10R to 10YR).

Clay contents ($g\,kg^{-1}$) were estimated in the field by "fingering". Soil pH (pH-H_2O) values for the Araras and Passo Fundo regions were determined with a pH meter in the laboratory; in the Assis region the pH was determined in the field, with Bromocresol Green, Bromothymol Blue and Chlorophenol Red indicator fluids (Weast, 1974, p. D115-116). pH was determined without completely drying, crushing and sieving the soil, because a preliminary study had shown that the variance introduced by partly omitting pretreatment of the samples was negligible.

4.2.2 Overall sampling

Field methods

Soil samples were taken by auger, according to a previously designed sampling scheme in order to prevent bias. Neighbouring sampling sites were 250-300 m apart. This resulted in 6 to 26 sampling sites per field. The distribution of sampling sites was as uniform as possible, but they were not arranged in a regular grid, because the fields were irregularly shaped. Sites in sugarcane fields had to be close to tracks (never closer than 25 m) because of difficult access and orientation in the high and dense sugarcane. In total 492 sites were included. Samples were taken from two depths: 0-20 m and 60-80 cm, resulting in 2x492=984 samples that were described in the field and analysed in the laboratory. Samples were always taken between the plant rows, when present.

Geographical locations (in UTM co-ordinates) and elevations above mean sea level (ALT, m) of the sampling sites in the Araras region were read from 1 : 10 000 topographic maps (Terrafoto, 1978/1980) coordinates of sites in the Assis and Passo Fundo regions were determined by using 1 : 50 000 maps (IBGE, 1973/1975; Ministério do Exercito, 1979), complemented by 1 : 5 000 and 1 : 10 000 maps, provided by the estates/farms and, in Assis, 1 : 35 000 air photographs (IGC, 1984). Information in the Passo Fundo region was insufficient for accurate determination of elevation at each sampling site.

Slope angles (SL, $cm\,m^{-1}$) were estimated in the field with a simple pocket device. This was not possible in fields with a dense stand of sugarcane where slopes were estimated from the 1 : 10 000 and 1 : 5 000 topographical maps.

Colour hues were transformed to numerical values as described above for the nested sampling.

4.2.3 Laboratory methods

Resin extractable phosphorous (P, $mg\,kg^{-1}$) was determined according to Raij & Quaggio (1983) by extraction with the "ion exchange resin". Laboratory methods for determining other analysed soil properties are described by Camargo et al (1986): clay content (particle size fraction <2 µm, $g\,kg^{-1}$) with the pipette method and dispersion with sodium hexametaphosphate and NaOH; pH in soil:solution suspension 1:2.5 KCl 1 $mol\,L^{-1}$; organic carbon (C, $g\,kg^{-1}$) by oxidation with potassium bichromate (slightly modified Walkley-Black); sum of exchangeable bases, SB (= Ca + Mg + K + Na, $mmol_c\,kg^{-1}$) extracted with NH_4OAc 1 $mol_c\,L^{-1}$ at pH 7. The cation exchange capacity (CEC, $mmol_c\,kg^{-1}$) was calculated as the sum of SB, plus potential acidity (H+Al, $mmol_c\,kg^{-1}$) extracted with calcium acetate 1 $mol_c\,L^{-1}$ at pH 7 and titration with NaOH, 0.1 $mol\,L^{-1}$. The percentage aluminium saturation (Al%) was calculated as 100% Al/(SB+Al), where Al is exchangeable acidity ($mmol_c\,kg^{-1}$) extracted with 1 $mol\,L^{-1}$ KCl and titration with NaOH 0.1 $mol\,L^{-1}$. The base saturation percentage (V) was calculated as 100%.SB/CEC.

4.2.4 Statistical analysis

The module NEST of the PC-GEOSTAT software package (Burrough & van Keulen, 1987) was used to compute the nested analysis of variance. SYSTAT (Systat Inc., 1985) was used to calculate averages, variances, skewnesses and kurtoses of the data of the overall sampling; and to execute one-way analysis of variance of soil characteristics within and between fields for the observations of the overall sampling. The percentage of total variance explained by division into fields was calculated as $100\%.(1-s_{field}^2/s_{tot}^2)$, where s_{field}^2 is the estimated pooled within-field variance of the variable of interest and s_{tot}^2 refers to the estimated total variance of the same variable in all study fields of the region. The program SEMVAR, adapted from SEMIVA of the PC-GEOSTAT package (Burrough & van Keulen, 1987), was used for semivariance analysis. This program determines γ as a function of I_{lag} from all data-pairs between $(I_{lag}-1)*d$ and $I_{lag}*d$ apart, where I_{lag} is an integer value ≥ 1

and d was set to 0.4 km. E.g for I_{lag}=1 all data-pairs between 0.0 and 0.4 km apart were considered; for I_{lag}=2 all data-pairs between 0.4 and 0.8 km apart, etc... Note that these programs have all been replaced by more modern ones, using the same logic (see Pebesma & Wesseling, 1998).

4.3 Results

4.3.1 Nested analysis of variance

Figures 4.2, 4.3 and 4.4 summarise the results of the nested analysis of variance for the Araras, Assis and Passo Fundo regions respectively. The average distances between sampling sites at each level are indicated on the abscissa and the cumulative variances on the ordinates.

Araras

With the exception of those for penetrometer resistance, the variograms for the Araras region (figure 4.2) are rather similar: the variance increases slightly from the shortest sampling interval (50 m) to 600 m, followed by a considerable increase from the 600 m interval to the between field level. The main difference between the spatial behaviour of the different soil attributes is the variance at the lowest sampling level (nugget variance). The nugget variance is extremely small for clay content, small for colour hue and relatively large for pH, chroma and value.

The variogram for penetrometer resistance indicates that all spatial levels contribute to the overall variance. The proportion of the variance found over short ranges is a considerable part of the total variance: about 40% of the within field variance is present within the 1.5x1.5 m^2 and 60% at the 50 m level. However, absolute levels of variance within and between fields seemed not very large.

Assis

Variograms of clay percentage (figure 4.3) are similar to those of the Araras region. Fields are uniform, but between-field-variance is large. A considerable increase of variance is noted from the 350 m to the 750 m level. The highest clay contents were estimated (in the field) at 650 g kg^{-1} in both layers. The soil with least clay had approximately 100 g kg^{-1} clay in the 0-20 cm layer and 160 g kg^{-1} in the 60-80 cm layer.

Variance of pH increases continuously with sampling level and suggest different spatial behaviour for the 0-20 cm layer and 60-80 cm layer.

The studied soils in the Assis region present much less variation in colour than the soils in the Araras region. Colours in Assis range from 10R2/3 to 2.5YR 3/6 in the 0-20 cm layer; and from 10R 3/3 to 2.5YR 4/6 in the 60-80 cm layer.

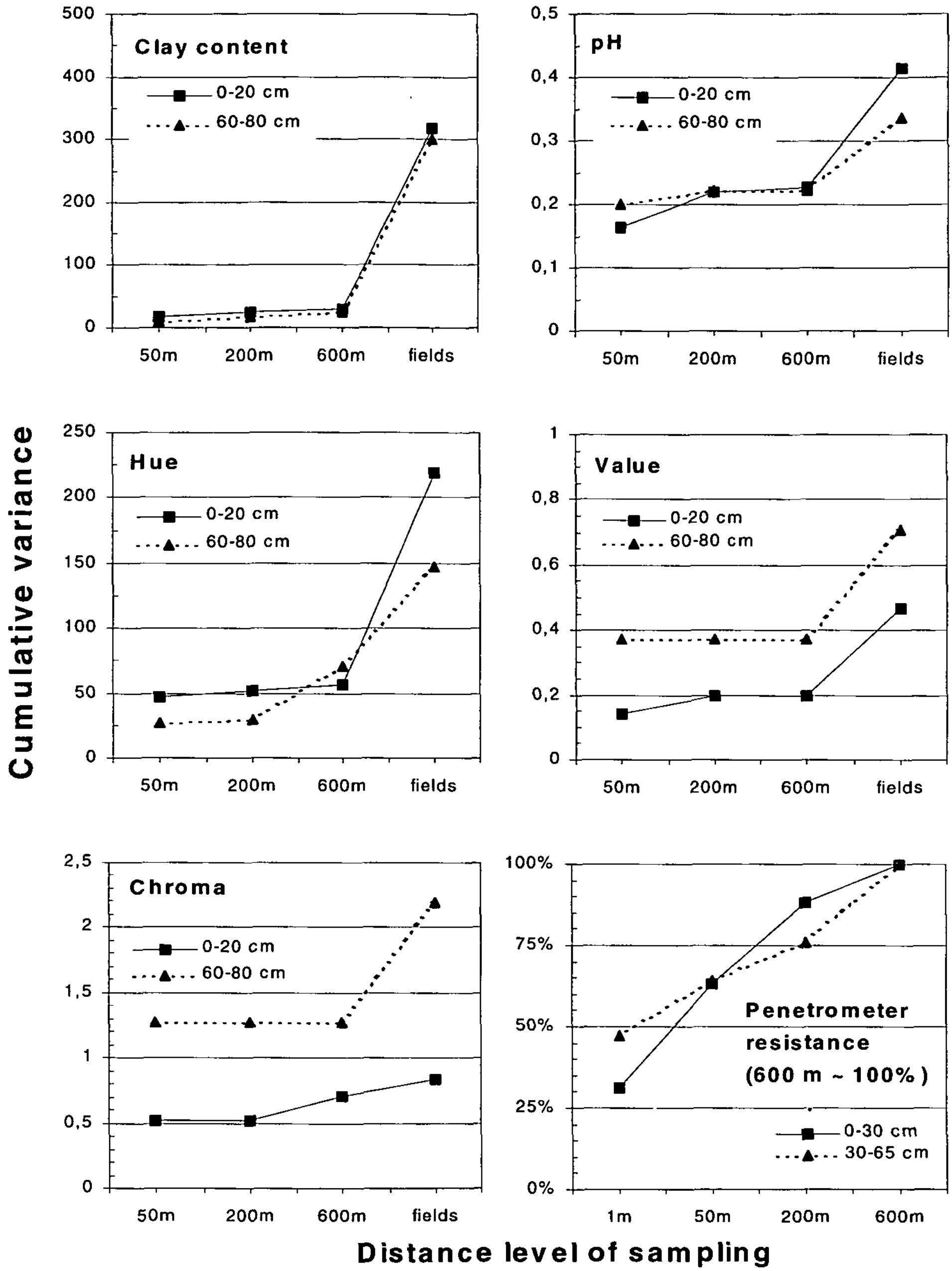


Figure 4.2 Nested variograms for the Araras region

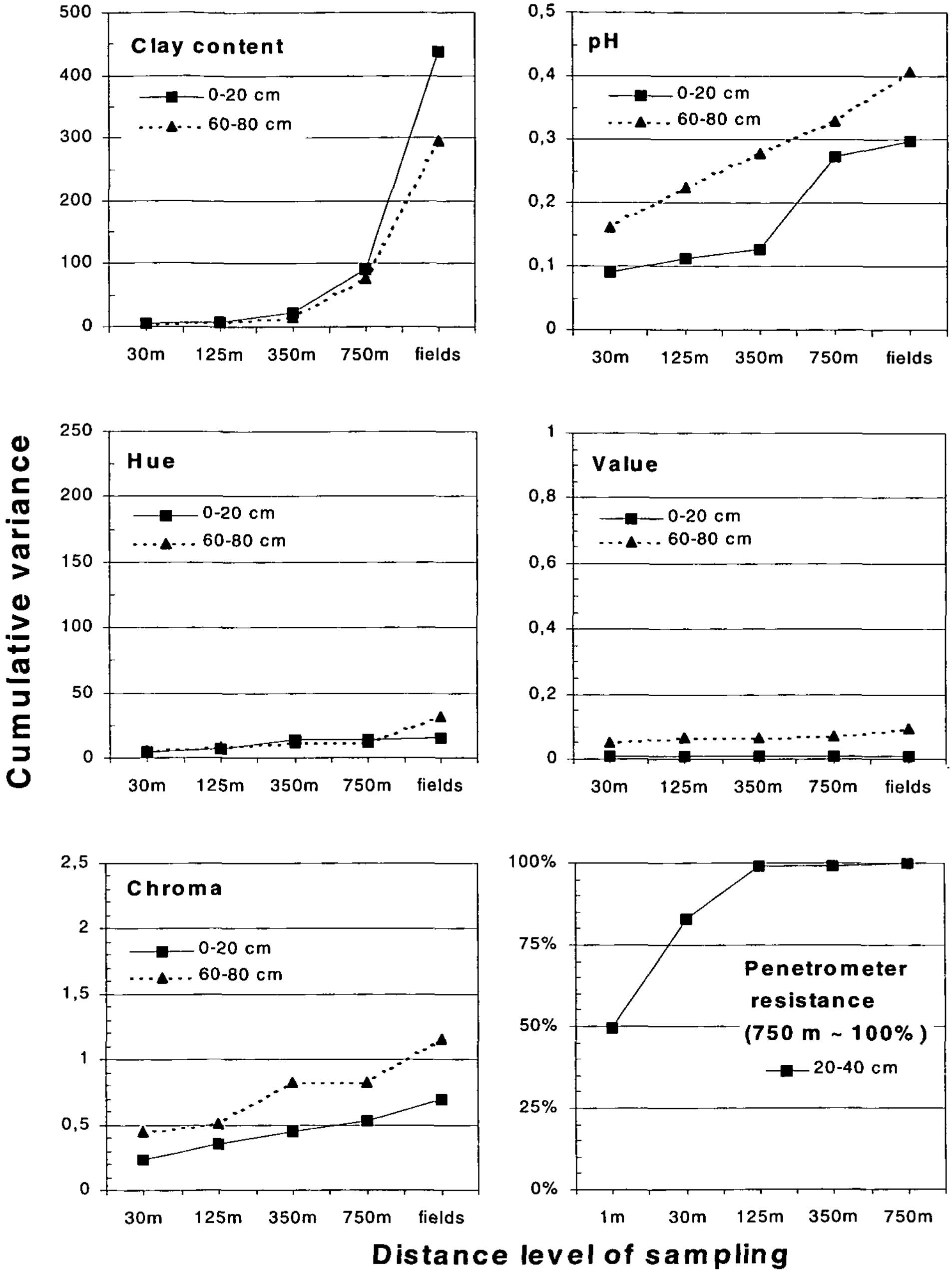


Figure 4.3 Nested variograms for the Assis region

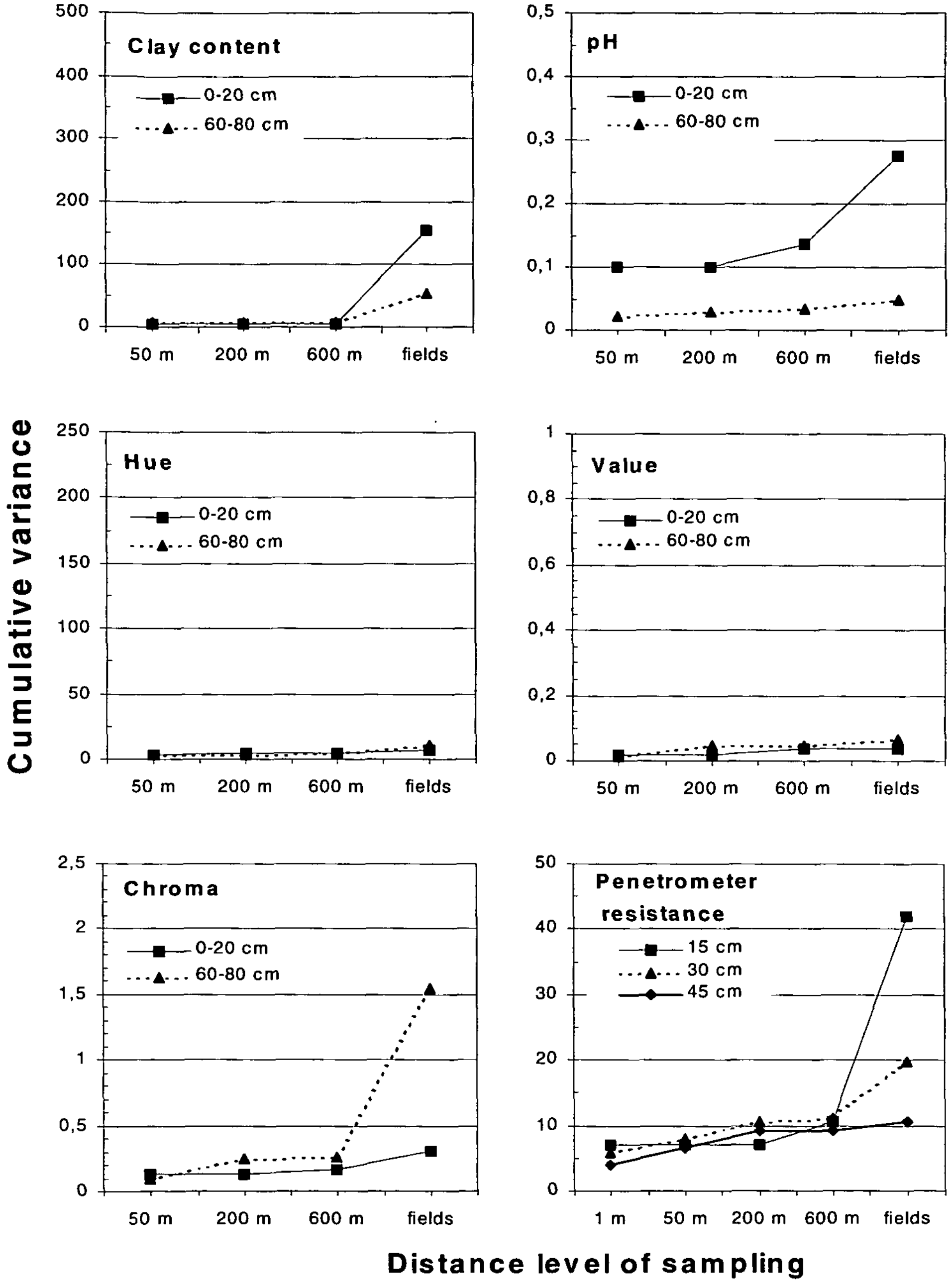


Figure 4.4 Nested variograms for the Passo Fundo region

The variogram of penetrometer resistance shows very large proportions of the variability at short distance. 50% of the within-field-variance is present within 1.5x1.5 m^2 and 80% within 30 m distance.

Passo Fundo

The shapes of the variograms for the Passo Fundo region (figure 4.4) resemble those of the Araras region; they differ mainly in nugget variance, that is very small for clay content, small for colour chroma and relatively large for pH. The variances in colour hue and value in the Passo Fundo region are about 10 times less than in the Araras region. The small variance of pH at 60-80 cm depth (0.034 at 600 m level) may reflect mainly analytical errors.

The variograms of penetrometer resistance show similar within-field variances for the three depths. About 70% of the within-field variance is present within 50 m. Most of this (all for the 15 cm depth) is present within 1.5 m. Recall that the observations at that level were calculated as the average value of three observations at the 20 cm level. Between-field variance in penetrometer resistance decreases with increasing depth. This suggests that the between-field variance is largely caused by differences in management stage. Some of the fields were under wheat at the moment of observation, others were under oat-pasture or recently ploughed. The statistically insignificant (at 5% level) difference between fields at the 45 cm depth suggests that differences in management stage had no influence at this depth. This does not exclude the possibility that long term management practices - which are similar for all study fields in the region - do influence penetration resistance at this depth.

4.3.2 Analysis of overall sampling

Statistical analyses of the data of the overall sampling are given in table 4.1 for the Araras region; in table 4.2 for the sugarcane fields of the Assis region, in table 4.3 for the soybean fields of the Assis region and in table 4.4 for the Passo Fundo region.

Araras

General statistics (table 4.1, part A). The average percentage Al-saturation is considerably greater in the 60-80 cm layer than in the 0-20 cm layer, whereas V%, C, P, SB and CEC are greater in the upper 20 cm.

Semivariance analysis Table 4.1, part B shows that the bulk of the within-field variance is present within 0.3 km for all variables except elevation above mean sea level (ALT) and P content. No spatial structure was detected (in the analysed range) of most variables of the 60-80 cm layer and of several of the 0-20 cm layer.

Analysis of variance by field. Total variance exceeds within-field variance significantly for all variables, except P of the 60-80 cm layer (table 4.1, part C). Division into fields resolved more than 90% of total variance in altitude (ALT) and clay content, and more than 50 % of the variance in sum of bases (SB) and cation exchange capacity (CEC) at both depths; and in organic C content of the 0-20 cm layer and in pH-KCl, base saturation (V%) and Al-saturation of the 60-80 cm layer.

Effect of log transformation. In a number of cases, skewness and kurtosis of the residuals from analysis of variance showed strong deviations from 0 (table 4.1, part D). Parts E-G of table 4.1 show that variables with strongly skewed or kurtic distributions (notably P) obtain a much "more normal" distribution after log transformation. Log transformation reduces the effect of outliers and the variance among fields becomes more homogeneous. The variance accounted for by division into fields did not change much for most characteristics. An exception was P (0-20 cm) for which the relative within-field variance was strongly reduced, and the variance accounted for increased from 19% to 52%, thanks to the "smoothing" effect of transformation on outliers.

Assis

General statistics. Part A of tables 4.2 and 4.3 show that sugarcane and soybean/-wheat fields have soils with similar average CEC and clay and organic C contents, in both analysed layers. Average P-content, pH, and base saturation of the 0-20 cm layer are much higher in the soybean/wheat fields than in the sugarcane fields.

Semivariance analysis. One can verify from part B of tables 4.2 and 4.3 that semivariances of most soil characteristics of the 0-20 cm layer of the soybean/wheat fields are considerably less than those of the sugarcane fields. Semivariance of the 60-80 cm layer is generally similar for sugarcane and soybean/wheat fields (major exceptions are C-content and P). Results for large lag values show some irregular jumps or falls.

Analysis of variance by field. Part C of tables 4.2 and 4.3 show that a very large proportion (>90%) of the variance in clay content is accounted for by the division into fields. It accounts for more than 50% of the variance of slope, SB and CEC of both analysed layers, C content of the 0-20 cm layer and V%, Al% and pH of the 60-80 cm layer. Note the large differences in variance in pH and V% of the 0-20 cm layer between soils with soybean/wheat rotation and soils with sugarcane.

Effect of log transformation. Several variables have strongly skewed or kurtic distributions (Part D of tables 4.2 and 4.3). Differences between the 0-20 cm and 60-80 cm layers become less evident after log transformation (like in the Araras region) because it leads to comparison of relative rather than absolute values. The log transformation seems appropriate for SB, CEC and Al%. For C, distributions became more "normal" after log transformation for the soybean fields, but more negatively skewed for the 0-20 cm layer of the sugarcane fields.

Passo Fundo

General statistics. Part A of table 4.4 shows for most characteristics similar differences between 0-20 cm and 60-80 cm layers as for the Araras and Assis regions, but differences in clay contents, pH and Al saturation between the analysed layers are more accentuated in Passo Fundo.

Semivariance analysis. The differences between γ for the 0.3 km and 0.6 km lags are generally small, as in the Araras and Assis regions. Semivariance shows strange "jumps" or "falls" at larger spatial levels, e.g. for SB and V% of the 60-80 cm layer and Al% of the 0-20 cm layer.

Analysis of variance by field. More than 85% of the total variance in clay content is accounted for by the division into fields (Table 4.4, part C). Variance in other soil characteristics of the 0-20 cm layer accounted for is also considerable, but division into fields explains much less variance in characteristics of the 60-80 cm layer. This reflects the overall uniformity of subsoil characteristics in the region. For most variables, even the pooled within-field variance is less at 60-80 cm than at the 0-20 cm depth.

Effect of log transformation. Log transformation seems appropriate for SB, Al% (0-20 cm) and V% (60-80 cm). In some cases the transformation leads to considerably different results. For example, 53% of the variance in Al% of the 0-20 cm layer was accounted for by the division into fields. This percentage increased to 69% after transformation, but for the same characteristic at the 60-80 cm depth, the variance accounted for decreased from 47% to 25%.

4.4 Discussion

4.4.1 Comparison of Nested analysis of variance with Semivariance

For the Araras region, semivariance and analysis of variance by field agree well with the nested analysis of variance. This agreement was less good for the other regions, especially Assis. Results of nested sampling yielded apparently too high estimates for within field variance of clay content and pH (60-80 cm) and for total variance of colour hue in the Assis region; and the semivariograms did not confirm the nested variance jump, from the 350 m to the 750 m level for pH (0-20 cm), suggested in figure 4.3. Most of these discrepancies are probably due to the limited number of fields analysed by the nested sampling. Recall that only four fields were analysed in Assis, vs. seven in Araras and Passo Fundo. The increase in variance detected for pH and clay content at the 750 m level in Assis is mainly the result of a single soil border that was detected across one of the fields.

Nevertheless, the general structure of the nested variograms agrees with the semivariograms that are based on a much more intensive sampling. The conclusion is that nested sampling can quickly provide a rough indication of spatial patterns, on which the density of a uniform sampling can be based. Nested analysis cannot claim more than that, if only few samples are taken. If a denser sampling is feasible, linear or grid sampling are preferred, because these provide a more uniform cover of the survey area and sites are easier to locate. Corsten & Stein (1991) came to a similar conclusion when comparing results of interpolation in several spatial sampling designs.

Table 4.1 Summary of statistical analysis of soil characteristics of the fields in the Araras region (15 fields, 166 sites)

Terrain and 0 – 20 cm	ALT	SL	Colour Hue	Chr	Clay	pH KCl	SB	CEC	Al	V	C	P
	m	cm m^{-1}			g kg^{-1}		mmol$_c$ kg^{-1}		%	%	g.kg^{-1}	mg.kg^{-1}
A. General statistics												
Minimum	607	0	30	1.0	20	3.7	4	9	0	11	2	1
Maximum	790	20	60	6.0	680	6.5	105	142	63	97	26	353
Algebraic mean	672	5	39	3.1	354	4.7	33	66	14	47	12	19
Geometric mean	671	4	39	3.0	283	4.7	25	59	5	42	11	11
B. Semivariance analysis												
γ(0.3)	62	7.4	22	0.5	2.3'	.16	145	116	185	204	8	369
γ(0.6)	118	7.4	28	0.4	2.7'	.19	177	145	222	246	10	995
γ(1.0)	206	8.4	37	0.4	3.9'	.22	237	196	251	299	12	561
γ(1.4)	235	8.4	29	0.5	4.6'	.24	299	329	336	284	16	2459
C. Analysis of variance within and between fields												
Total Var.	1868	14	50	.73	38.0'	.32	558	858	310	417	27	1131
field Var.	136	8	31	.43	3.0'	.20	188	161	226	256	10	919
%Var. explained	93	43	38	41	92	37	66	81	27	39	63	19
D. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	0.6	0.8	0.6	0.1	0.3	0.3	1.1	0.3	1.2	-0.2	0.3	6.0
Kurtosis	0.5	1.7	0.6	0.6	1.5	1.2	3.1	0.8	2.1	1.1	0.7	56.6
Log-transformed data: *E. Semivariance analysis*												
γ(0.3)	-	.30	.013	.046	.067	.006	.16	.046	1.3	.14	.12	.33
γ(0.6)	-	.36	.016	.053	.052	.008	.20	.046	1.9	.16	.13	.39
γ(1.0)	-	.41	.021	.048	.048	.009	.23	.048	2.4	.18	.14	.40
γ(1.4)	-	.58	.014	.060	.036	.010	.23	.063	2.1	.17	.19	.81
F. Analysis of variance within and between fields												
Total Var.	3.9'	.82	.030	.088	.575	.014	.59	.266	3.1	.25	.31	.86
Field Var.	.29'	.39	.017	.050	.058	.008	.21	.049	1.9	.16	.13	.41
%Var. explained	93	51	43	43	90	43	64	81	39	36	58	52
G. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	0.2	-0.1	0.4	-0.8	-0.6	0.2	-0.3	-0.3	0.1	-0.9	-0.6	0.7
Kurtosis	0.3	0.3	0.4	1.9	9.0	0.7	0.7	2.7	0.3	1.8	3.4	2.3
60 – 80 cm												
A. General statistics												
Minimum	-	-	30	1.0	40	3.8	1	6	0	6	0	1
Maximum	-	-	60	8.0	780	6.1	81	137	91	83	22	34
Algebraic mean	-	-	39	4.9	396	4.6	18	47	32	33	6	2.5
Geometric mean	-	-	38	4.6	324	4.5	12	42	13	28	5	1.7
B. Semivariance analysis												
γ(0.3)	-	-	20	1.0	2.6'	.10	79	112	227	128	4	10
γ(0.6)	-	-	27	1.4	3.2'	.12	88	145	296	168	7	12
γ(1.0)	-	-	36	1.4	4.3'	.11	78	133	259	177	7	17
γ(1.4)	-	-	36	1.9	4.3'	.06	57	127	162	113	13	9
C. Analysis of variance within and between fields												
Total Var.	-	-	47	1.9	45.4'	.24	283	525	699	340	11	15
Field Var.	-	-	30	1.3	3.4'	.11	77	131	256	156	6	14
%Var. explained	-	-	37	32	93	54	73	75	63	54	45	7
D. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-	0.7	0.2	0.6	1.1	0.8	0.5	-0.5	0.6	0.8	5.0
Kurtosis	-	-	0.9	0.4	2.3	2.7	2.6	1.6	1.4	1.3	2.5	32.0
Log-transformed data: *E. Semivariance analysis*												
γ(0.3)	-	-	.011	.061	.056	.004	.22	.065	1.0	.13	.20	.39
γ(0.6)	-	-	.015	.066	.050	.005	.25	.063	1.3	.17	.26	.42
γ(1.0)	-	-	.020	.065	.053	.005	.24	.060	1.3	.16	.26	.39
γ(1.4)	-	-	.016	.105	.032	.002	.12	.043	0.8	.12	.39	.42
F. Analysis of variance within and between fields												
Total Var.	-	-	.027	.098	.505	.011	.80	.248	3.3	.33	.40	.51
Field Var.	-	-	.016	.068	.055	.005	.23	.064	1.2	.16	.25	.42
%Var. explained	-	-	41	31	89	55	71	76	64	52	38	18
G. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-	0.5	-0.7	-0.1	1.0	0.2	-0.5	-0.8	-0.1	-0.6	0.7
Kurtosis	-	-	0.3	2.2	5.6	2.6	1.4	4.1	2.8	0.7	2.8	3.8

' multiply values by 10^3

Table 4.2 Summary of statistical analysis of soil characteristics of sugarcane fields in the Assis region (11 fields, 167 sites)

Terrain and 0 – 20 cm	ALT	SL	Colour Hue	Chr	clay	pH KCl	SB	CEC	Al	V	C	P
	m	cm m^{-1}			g kg^{-1}		mmol$_c$ kg^{-1}		%	%	g kg^{-1}	mg kg^{-1}
A. General statistics												
Minimum	370	0	22	2.0	50	4.0	4	16	0	10	3	1
Maximum	566	13	50	4.0	760	6.6	221	243	74	100	31	214
Algebraic mean	460	4	29	3.1	437	4.9	47	72	8	61	13	13
Geometric mean	-	3	29	3.0	334	4.9	34	59	3	58	11	8
B. Semivariance analysis												
γ(0.3)	104	3.2	7	.10	2.9'	.20	678	621	114	231	10	255
γ(0.6)	217	5.2	7	.10	4.7'	.23	781	662	147	272	11	212
γ(1.0)	327	6.9	8	.11	6.7'	.22	888	738	107	264	11	115
γ(1.4)	365	12.3	12	.12	8.8'	.19	1361	1147	103	241	12	91
C. Analysis of variance within and between fields												
Total Var.	2775	7.6	8	.12	68.3'	.26	1408	1878	146	322	42	409
field Var.	237	5.1	5	.11	4.2'	.23	669	573	118	257	11	308
%Var. explained	91	34	34	12	94	10	52	70	20	20	74	25
D. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-2.8	0.3	5.0	0.6	-2.2	0.7	2.0	2.3	2.4	-0.3	-0.3	-
kurtosis	20.9	1.3	47.1	2.6	17.6	0.8	9.5	12.3	9.2	0.2	4.2	-
Log-transformed data:												
E. Semivariance analysis												
γ(0.3)	-	.32	.007	.012	.031	.008	.26	.069	1.2	.10	.059	.40
γ(0.6)	-	.51	.007	.012	.046	.009	.32	.082	1.5	.12	.070	.35
γ(1.0)	-	.61	.007	.012	.064	.009	.33	.104	1.4	.11	.078	.51
γ(1.4)	-	.78	.011	.012	.076	.007	.31	.099	1.1	.10	.062	.42
F. Analysis of variance within and between fields												
Total Var.	-	.63	.009	.014	.658	.010	.71	.427	1.8	.129	.342	.85
field Var.	-	.49	.007	.012	.050	.009	.28	.081	1.3	.105	.073	.47
%Var. explained	-	23	19	14	92	9	60	81	29	19	79	45
G. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-1.0	1.2	0.0	-1.2	0.4	-0.4	0.5	0.2	-1.4	-0.9	-
Kurtosis	-	1.2	12.4	3.4	8.9	0.4	1.9	1.9	-0.4	4.1	2.9	-
60 – 80 cm												
A. General statistics												
Minimum	-	-	26	3.0	100	3.9	0	.9	0	1	1	0
Maximum	-	-	40	6.0	830	6.1	138	141	97	98	25	51
Algebraic mean	-	-	30	4.1	506	4.7	29	49	26	48	6	4
Geometric mean	-	-	30	4.1	420	4.7	16	42	8	38	6	3
B. Semivariance analysis												
γ(0.3)	-	-	2	.15	1.1'	.14	200	142	145	190	5.7	17
γ(0.6)	-	-	2	.15	2.0'	.16	257	195	191	259	7.6	15
γ(1.0)	-	-	3	.12	3.3'	.21	297	193	207	324	8.2	17
γ(1.4)	-	-	3	.13	4.8'	.19	425	300	99	275	5.6	8
C. Analysis of variance within and between fields												
Total Var.	-	-	2	.20	67.6'	.43	653	647	812	671	12.6	22
field Var.	-	-	2	.15	2.3'	.16	230	161	203	254	6.6	19
%Var. explained	-	-	18	29	97	62	65	75	75	62	48	11
D. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-	4.6	1.4	0.2	0.2	1.0	1.0	0.2	0.1	2.6	-
kurtosis	-	-	38.5	8.2	4.4	0.3	3.3	2.8	1.5	-1.5	12.1	-
Log-transformed data:												
E. Semivariance analysis												
γ(0.3)	-	-	.002	.008	.009	.005	.26	.044	.92	.19	.083	.32
γ(0.6)	-	-	.002	.008	.015	.006	.35	.063	1.19	.20	.108	.32
γ(1.0)	-	-	.003	.006	.023	.008	.34	.060	1.33	.17	.123	.41
γ(1.4)	-	-	.003	.006	.024	.007	.28	.072	1.02	.11	.086	.27
F. Analaysis of variance within and between fields												
Total Var.	-	-	.003	.010	.444	.019	1.54	.326	3.26	.61	.299	.48
field Var.	-	-	.002	.007	.018	.007	.33	.053	1.14	.20	.104	.35
%Var. explained	-	-	20	28	96	65	79	84	65	67	65	27
G. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-	2.6	0.6	0.5	0.7	-0.4	0.1	-0.4	-1.0	-0.1	-
Kurtosis	-	-	19.0	6.1	1.6	4.1	0.4	0.4	1.0	2.7	2.6	-

' multiply values by 10^3

Table 4.3 Summary of statistical analysis of soil characteristics of soybean fields in the Assis region (7 fields, 62 sites)

Terrain and 0 – 20 cm	ALT m	SL cm m^{-1}	Colour Hue	Chr	clay g kg^{-1}	pH KCl	SB mmol$_c$ kg^{-1}	CEC	Al %	V %	C g kg^{-1}	P mg kg^{-1}
A. General statistics												
Minimum	310	0	26	3.0	150	4.6	21	28	0	52	3	3
Maximum	415	8	50	4.0	730	6.9	110	134	9	100	24	93
Algebraic mean	359	3	32	3.4	439	5.6	55	69	1	81	11	34
Geometric mean	-	2	32	3.4	374	5.6	50	62	0	80	10	29
B. Semivariance analysis												
γ(0.3)	38	0.6	10	.09	1.1'	.08	93	77	3	43	3	183
γ(0.6)	154	2.2	4	.07	1.7'	.06	122	99	3	39	5	218
γ(1.0)	411	4.8	3	.05	1.9'	.07	200	165	3	41	4	215
C. Analysis of variance within and between fields												
Total Var.	1020	7	16	.17	51.5'	.15	542	946	4	124	27	405
field Var.	n.d	2	8	.08	1.4'	.07	111	94	4	42	4	209
%Var. explained	-	70	48	53	97	53	80	90	8	66	87	48
D. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	0.2	0.9	0.3	-1.0	0.4	0.6	1.0	1.6	-0.9	1.3	0.9
kurtosis	-	-.5	3.1	1.0	2.7	1.5	0.7	1.8	4.5	1.2	2.5	0.6
Log-transformed data:												
E. Semivariance analysis												
γ(0.3)	-	.14	.008	.007	.009	.002	.03	.013	.62	.008	.025	.19
γ(0.6)	-	.46	.004	.006	.009	.002	.03	.013	.68	.007	.027	.22
γ(1.0)	-	.69	.003	.004	.015	.002	.04	.020	.56	.007	.015	.26
F. Analaysis of variance within and between fields												
Total Var.	-	1.16	.013	.014	.352	.005	.19	.224	.77	.019	.263	.40
field Var.	-	.41	.007	.007	.011	.002	.03	.014	.68	.007	.027	.22
%Var. explained	-	65	51	54	97	53	84	94	11	63	90	44
G. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-.1	0.5	0.2	-0.7	0.0	-0.1	0.5	0.4	-1.1	0.1	-0.6
Kurtosis	-	-1.4	2.0	-1.4	1.5	1.3	-0.3	-0.5	-0.5	1.6	0.1	1.5
60 – 80 cm												
A. General statistics												
Minimum	-	-	26	3.0	200	3.9	4	13	0	12	2	1
Maximum	-	-	50	6.0	780	6.3	76	93	72	97	11	11
Algebraic mean	-	-	31	4.0	530	5.2	31	46	13	63	5	3
Geometric mean	-	-	31	3.9	489	5.1	25	43	13	58	4	3
B. Semivariance analysis												
γ(0.3)	-	-	12	.26	1.1'	.16	98	70	178	234	.8	1
γ(0.6)	-	-	7	.26	2.1'	.31	177	108	262	418	1.7	2
γ(1.0)	-	-	2	.16	1.8'	.21	183	179	59	174	3.5	5
C. Analysis of variance within and between fields												
Total Var.	-	-	14	.57	40.4'	.51	291	242	493	487	3.7	3
field Var.	-	-	10	.28	1.7'	.24	134	95	224	324	1.5	2
%Var. explained	-	-	30	52	96	53	54	61	55	33	59	15
D. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-	1.8	0.5	-0.8	-0.2	0.6	1.3	1.0	-0.4	1.3	2.4
kurtosis	-	-	6.3	0.3	1.7	0.5	0.9	3.0	2.8	0.0	2.4	8.3
Log-transformed data:												
E. Semivariance analysis												
γ(0.3)	-	-	.010	.014	.006	.006	.14	.035	0.9	.12	.047	.12
γ(0.6)	-	-	.007	.015	.011	.012	.23	.038	1.4	.17	.058	.15
γ(1.0)	-	-	.002	.010	.010	.008	.10	.043	0.8	.05	.107	.40
F. Analaysis of variance within and between fields												
Total Var.	-	-	.013	.039	.180	.021	.55	.13	3.2	.23	.184	.22
field Var.	-	-	.008	.015	.010	.010	.18	.04	1.1	.15	.065	.17
%Var. explained	-	-	34	62	94	55	67	71	66	37	65	21
G. Skewness, Kurtosis of residuals (measured values – field averages)												
Skewness	-	-	1.0	0.5	-0.5	-0.3	-0.7	-0.1	0.5	-0.7	0.5	0.1
Kurtosis	-	-	3.8	0.1	0.5	0.6	0.6	1.8	0.4	0.9	0.0	-0.2

' multiply values by 10^3

Table 4.4 Summary of statistical analysis of soil characteristics of the fields in the Passo Fundo region (6 fields, 97 sites)

Terrain and 0 – 20 cm	SL	Colour Hue	Chr	clay	pH KCl	SB	CEC	Al	V	C	P
	$cm\ m^{-1}$			$g\ kg^{-1}$		$mmol_c\ kg^{-1}$		%	%	$g\ kg^{-1}$	$mg\ kg^{-1}$
A. General statistics											
Minimum	0	32	2.5	210	3.7	14	28	0	27	10	16
Maximum	20	48	4.0	720	6.0	177	183	47	99	27	353
Algebraic mean	8	39	3.2	480	4.8	75	109	9	66	17	62
Geometric mean	7	38	3.2	450	4.8	65	103	4	63	17	55
B. Semivariance analysis											
$\gamma(0.3)$	18.6	3	.06	2.1'	.11	410	300	60	162	4	1471
$\gamma(0.6)$	21.9	3	.08	2.6'	.12	440	290	63	173	4	2325
$\gamma(1.0)$	17.0	4	.08	3.3'	.14	460	310	37	169	5	1403
$\gamma(1.4)$	17.8	4	.07	2.6'	.12	410	320	33	162	5	1064
C. Analysis of variance within and between fields											
Total Var.	22.0	10	.09	24.1'	.35	1430	1060	133	337	12	1612
field Var.	19.0	4	.08	2.6'	.11	390	310	62	173	4	1535
%Var. explained	14	62	14	89	68	73	71	53	49	65	5
D. Skewness, Kurtosis of residuals (measured values – field averages)											
Skewness	0.0	0.0	0.3	-0.5	0.1	0.6	0.1	1.1	0.4	0.7	4.2
kurtosis	-0.1	-0.3	-0.6	-1.2	-0.2	1.8	-0.1	3.8	0.0	1.0	24.7
Log-transformed data:											
E. Semivariance analysis											
$\gamma(0.3)$	.58	.002	.006	.012	.004	.07	.043	.69	.05	12	.20
$\gamma(0.6)$	.62	.002	.008	.014	.005	.07	.040	.77	.05	13	.22
$\gamma(1.0)$	.44	.003	.008	.013	.006	.07	.043	.65	.04	14	.23
$\gamma(1.4)$	.42	.003	.006	.009	.005	.06	.043	.88	.04	16	.29
F. Analaysis of variance within and between fields											
Total Var.	.58	.006	.008	.140	.015	.32	.140	2.24	.10	45	.24
field Var.	.53	.003	.007	.014	.005	.07	.049	.70	.05	14	.22
%Var. explained	9	60	13	90	69	78	65	69	48	69	9
G. Skewness, Kurtosis of residuals (measured values – field averages)											
Skewness	-1.2	-0.1	0.1	-0.4	0.0	-0.2	-1.2	0.0	0.1	0.3	0.2
Kurtosis	1.2	-0.4	-0.6	-1.1	-0.2	0.5	3.0	0.3	1.1	0.8	1.2
60 – 80 cm											
A. General statistics											
Minimum	-	30	3.5	380	3.8	5	54	3	8	4	1
Maximum	-	46	6.0	820	4.9	68	115	89	73	11	11
Algebraic mean	-	33	5.2	650	4.2	23	75	51	30	8	3
Geometric mean	-	33	5.2	630	4.2	20	74	43	27	8	3
B. Semivariance analysis											
$\gamma(0.3)$	-	2	.24	1.9'	.02	120	90	198	110	2.1	2
$\gamma(0.6)$	-	2	.22	2.7'	.03	110	90	229	121	2.3	2
$\gamma(1.0)$	-	3	.22	2.4'	.04	150	110	267	152	2.7	2
$\gamma(1.4)$	-	2	.15	2.1'	.04	170	130	294	171	2.9	4
C. Analysis of variance within and between fields											
Total Var.	-	7	.56	17.9'	.04	170	120	422	195	2.3	2
field Var.	-	3	.23	2.6'	.03	120	100	225	125	2.3	2
%Var. explained	-	60	59	86	36	26	16	47	36	0	7
D. Skewness, Kurtosis of residuals (measured values – field averages)											
Skewness	-	1.3	-0.1	-0.8	1.9	1.0	0.8	-0.8	1.1	0.0	2.2
kurtosis	-	6.8	-0.7	1.4	5.4	3.2	1.5	0.2	1.1	-0.5	6.9
Log-transformed data:											
E. Semivariance analysis											
$\gamma(0.3)$	-	.002	.011	.006	.001	.15	.016	.34	.09	.034	.12
$\gamma(0.6)$	-	.002	.009	.008	.001	.17	.016	.36	.12	.037	.11
$\gamma(1.0)$	-	.002	.008	.006	.002	.19	.019	.47	.12	.044	.14
$\gamma(1.4)$	-	.002	.005	.005	.002	.20	.022	.54	.12	.054	.20
F. Analaysis of variance within and between fields											
Total Var.	-	6'	25'	50'	2'	.25	.021	.48	.21	38'	.14
field Var.	-	2'	10'	8'	1'	.17	.017	.36	.12	38'	.13
%Var. explained	-	63	60	84	38	32	16	25	50	0	9
G. Skewness, Kurtosis of residuals (measured values – field averages)											
Skewness	-	0.9	-0.1	-0.9	1.2	0.2	0.1	-2.0	0.3	-0.5	0.4
Kurtosis	-	4.0	-0.4	2.0	1.0	0.6	0.0	4.4	-0.1	0.4	1.0

' multiply values by 10^3

4.4.2 Comparison of semivariance with analysis of variance by field

For most characteristics of the study regions, within field variances are very close to the semi-variances at lags between 0.3 and 0.6 km. This does not necessarily mean that the range of spatial dependence is somewhere between 0.3 and 0.6 km, because the fields are of limited size. Semivariances for 1.4 km lag in sugarcane fields, and ≥1.0 km lag in soybean/wheat fields are not reliable. The number of data pairs seems sufficient - e.g. 98 for 1.4 km lag on sugarcane fields in Assis - but there are few truly independent observations (about 10), because many data pairs are located close to each other. This causes irregular semivariograms, like the ones for pH, Al%, V% and C of the 60-80 cm layer (Araras), SB of the 0-20 cm layer (Assis, sugarcane) and Al% of the 0-20 cm layer (Passo Fundo). The irregular semivariogram for P (Araras, 0-20 cm) is caused by a few outliers (note the large maximum value in table 4.1, Part A).

This suggests that, unless very dense sampling schemes are used, little is won by using interpolation methods that consider spatial dependence as proposed by Rugowski & Wolf (1994) and Boucneau et al. (1998). The fields in the present study can almost as well be described in classical terms of average and variance.

4.4.3 Effects of management on soil properties and their variability

There is little doubt that many differences between the 0-20 cm and 60-80 cm layer are enhanced by liming and fertilisation that had greater effect on the 0-20 cm layer than on the 60-80 cm layer. Differences in variance between the 0-20 and 60-80 cm layer are also influenced by management: liming has decreased exchangeable Al and percentage Al-saturation of the 0-20 cm layer of fields with acid soils. In this respect, fields have become less different from each other. In the case of pH and V%, variance within sugarcane fields is greater for the 0-20 cm layer than for the 60-80 cm layer, possibly because of uneven distribution of lime. In soils with very low CEC, Al saturation decreases to practically nil, irrespectively of the amount of lime applied, above a threshold value at say pH 5.5; whereas pH continues to increase with liming. The result is a large variance of pH and small variance of Al saturation in the surface layer of soils with sugarcane. Likewise, the within-field variance of P is very large in the surface soil, probably induced by uneven application of fertilisers.

It is too simplistic to conclude that soil management is responsible for short range soil variability. Variance levels of C-content, V% and CTC, reported in a recent study on soil variability in a natural remnant forest in the west of Sao Paulo State, (Sparovek & Camargo, 1997) are remarkably similar with those of the sugarcane fields in this study. Variance in P was considerably smaller in the unfertilised forest soils. The large short-range variability of other chemical surface soil characteristics mentioned by those authors was attributed to short-range differences in vegetation, resulting e.g. in strong variability in litter deposits. Management of a cropped soil apparently imposes modifications on spatial patterns, but this does not necessarily imply that soils under natural vegetation are more homogeneous.

The soybean/wheat fields generally have a better base status, higher pH, more P and less variability in the 0-20 cm layer than the sugarcane fields. These differences are probably caused by the more intensive management of soybean/wheat fields, with higher lime and P applications and smoothing by tillage of the topsoil. The soybean/wheat fields receive more P-fertiliser and lime because these crops require better P-availability and are less tolerant to soil acidity than the sugarcane cultivars used in South East Brazil. The soybean/wheat fields are ploughed and levelled twice a year. Tillage of sugarcane fields occurs on average only once in 6 years. In sugarcane fields lime and fertilisers are placed, whereas they are broadcast in soybean/wheat fields. The relatively small P-contents of the 60-80 cm layer reflect the small natural P content and the immobility of P in the soil, which precludes enrichment from the fertilised topsoil. Large maximum values and semi-variance for P at 60-80 cm depth in the sugarcane fields, may have been caused by deep ploughing before planting, a common practice in Brazilian sugarcane management. This occasionally may have contaminated the 60-80 cm layer of sugarcane fields with P-rich topsoil. Deep ploughing is not commonly practised in soybean management.

It is recognised that the comparison of sugarcane fields with soybean/wheat fields above is rather tricky. Study fields in the Assis region were not randomly distributed (figure 3.3). Therefore, effects of management could be confounded with pedological differences, even though similarities between the subsurface characteristics suggest that pedological differences are small.

4.4.4 Comparison of study regions

The study regions differ in several aspects: Overall soil variation as indicated by the number of previously mapped soil classes is much larger in Araras than in Assis and Passo Fundo, mainly due to a more complex pattern of contrasting parent materials in the Araras region. Nevertheless, in many cases, the shapes of the nested variograms and semivariograms and the results of the analysis of variance by field, are remarkably similar, notably with respect to more permanent soil characteristics, such as clay content, CEC and organic C content and even more so if the log transformed characteristics are compared. This suggests similar spatial structures of soil variability which may be characteristic for strongly weathered soils of South and South East Brazil. Additional studies are necessary to confirm this hypothesis. Note that there are also some important differences between the regions. For example V%, Al% and pH of the 60-80 cm layer show relatively large short distance variability for the soils in Araras and Assis and smaller variability for the Passo Fundo region, where all soils are acid, possibly as a result of its perhumid climate with more intensive leaching. Soil colour shows little variability in Assis and Passo Fundo and relatively large variability in the Araras region, with a considerable component at short distances, which seems to be related with the aforementioned complex pattern of contrasting often reworked parent materials in the Araras region.

4.4.5 Optimization of sampling

Two major spatial levels of soil variability appear to exist in the three regions of this study: (1) Long range (> 1 km) spatial variability correlated with interacting climate, parent material, former vegetation and major land use is dominant for durable soil characteristics like clay content, C content and CEC; and (2) short range spatial variability which seems to be conditioned by soil management, especially in case of easily modified characteristics of the surface soil, like P (fertilisation), V% and pH (liming). Spatial variability of intermediate range seems of minor importance. Hence, at a regional level (e.g. scale 1 : 100 000), soils in the three regions can be mapped with the same sampling density, although the amount of unresolved variation may vary between regions. For example, the large nugget variance for colour hue in Araras and pH in Araras and Assis indicate that drawing boundaries between e.g. Dark Red and Dusky Red Latosols, or eutrophic and distrophic soils, entails considerable error. These groupings can be mapped with little error in Passo Fundo.

Further research is necessary on spatial variation at intermediate range. The results of this study suggest that this is of minor importance, but it may be masked by the large variability at short range. Bulked sampling could possibly be used to level out short-range variation in order to visualise the medium range patterns, which could then be mapped without too much additional cost (see figure 7.1 of Burrough, 1991). Such bulked samples could consist of samples collected within an area of, say, 10 x 10 m^2.

4.5 Conclusions

1. The soil properties clay content, CEC and C content show similar spatial variability structure in the study regions. Variability of these characteristics is small at distances up to 1 km or more and large between fields at more than 1 km distance.

2. The soil properties pH, V% and Al% of the 0-20 cm layer and P of the 60-80 cm layer show large short distance variability for soils with sugarcane and smaller variability for soils with soybean/wheat rotation. These differences are apparently related to soil management.

3. Soil colour shows relatively large variability in the Araras region, with a considerable component at short distances. The variablity of soil colour is small in Assis and Passo Fundo.

4. Independent of the soil characteristic(s) of interest, a sampling density of 1 per 0.25 km^2 or less (0.5-1.0 km interval between nearest neighbours) is sufficient to resolve the major spatial patterns of strongly weathered soils in the studied areas. Variance of some soil characteristics within mapping units may still be considerable, depending on survey region and soil management. Increasing sampling density to 1 per 0.0025 km^2 (i.e. 50 m intervals) will result in little improvement of the quality of the soil survey.

5. Alternative sampling methods, e.g. bulking, must be studied to find out whether very short range variation can be filtered out for regional surveys.

6. The considerable variance of penetrometer resistance at very short distances ($\leq$ 1.5 m) indicates that determinations of soil-water relations, or soil-rootability relations should be made on large soil volumes, or sufficient replicates should be taken to establish adequate average values.

5. QUALITY OF SOIL MAPS IN THE SÃO PAULO STUDY REGIONS

5.1 Introduction

Existing soil maps are increasingly being used for purposes that the makers never had in mind. They are linked to GIS with overlays of other maps and "representative profiles" are used to represent mapping units in automated land evaluation studies etc... (e.g. De Koning & van Diepen, 1992; Rötter and Dreiser, 1994; Mantel & van Engelen, 1997). These new applications of soil maps call for increased awareness with regard to their quality. The quality of soil maps is traditionally taken care of by using experienced, well-trained surveyors, optimising observation density, sampling schemes and laboratory methods. The final result should be tested with an independent data set. This is often not done however, because it is expensive and, possibly, because the makers are so confident of their product that they believe additional tests are unnecessary.

Since the 1980's, many research efforts have been devoted to optimising sampling schemes and interpolation techniques for isorithmic maps (see reviews in e.g. Webster & Oliver, 1990, Burrough & McDonnell, 1998). These techniques are especially useful for detailed studies (say scale > 1:20 000) with a clear objective (e.g. the depth of a toxic layer). There has been much less research attention to the quality of so-called multi-purpose maps that use a choropleth representation. Several apparently straightforward methodologies are established (Beckett & Webster, 1971; Forbes et al., 1982; Marsman & de Gruijter, 1986; Oberthür et al, 1996), but not often applied. For Brazil, where only a minor part has been mapped at larger scale than 1 : 0.5M, just one reference was found to a study on soil map quality using independent data: Van den Berg & Klamt (1997) compared the soils in the 7 study fields of the Passo Fundo Region (RS) with a 1 : 1M map (see figure 3.4) and found none of them correctly described by the legend. Soils in six fields presented smaller Fe_2O_3 content and/or less reddish colour and soils in four fields presented smaller organic-C content than were indicated by the map.

The quality of choropleth maps cannot be indicated by a single rating. The ultimate criterion for the user is that the risk of taking a wrong decision based on map information should be small. In modern applications this implies that outcomes of models (e.g. for crop growth, erosion hazard) using the map as a source of input data may not give errors beyond acceptable proportions. This can only be assessed when the application of the map is clear *a priori*, which is typically not the case for multi-purpose maps. Other criteria to be considered include:

- **User-friendliness.** Soil maps are by definition a simplification of the field situation. One of the "arts" of mapping is to optimise the balance between providing maximum information without becoming too complex for the user. The problem of complexity measures will not be addressed here. Interested readers are referred to Bregt & Wopereis (1990).
- **Relevance of provided information**. This depends on the objectives of the user; e.g. a soil fertility map is of little use to road engineers. Legends of many soil maps

are based on taxonomic considerations, which are often related to the presumed formation of soils. In such cases, interpretation on land use potential and management properties can only be done after correlating mapping units with land qualities.

- **Purity and homogeneity of mapping units**. These can be assessed by the soil survey team, by analysis of an independent data set, e.g. just after finishing the map. Some publications use the broader terms "accuracy" and "precision", but these are not consistently defined (cf. Marsman & de Gruijter, 1986, p. 37 vs. Arnold, 1996). Purity refers to the degree of correspondence between indications on the soil map and ground truth. Homogeneity of mapping units can be determined statistically by the (pooled) within mapping units variance of soil properties. Whether mapping units are more homogeneous than the total mapped area can be assessed with analysis of variance.

The objectives of this Chapter are: (1) to quantify the heterogeneity of apparently homogeneous mapping units with strongly weathered soils in the study regions of São Paulo State, in terms of purity and resolved variance of soil variables; (2) to assess the utility of the soil maps for agricultural land evaluation; and (3) to suggest possibilities for economically feasible improvements of soil map quality.

For this purpose, we analysed semi-detailed (scale 1 : 100 000) soil maps of the study regions in São Paulo State (Araras and Assis), where soil data from the 33 apparently homogeneous sugarcane and soybean/wheat fields were compared with existing soil maps.

For the Passo Fundo region, it was felt that the scale of sampling used for this study (250-300 m between adjacent sites) was incompatible with the scale of existing soil maps in that region ($\leq$ 1:750 000). Therefore map unit information was compared with the soil data of Chapter 4 plus 7 additional soil profiles, by considering the study fields as a whole. Results are reported in the aforementioned study of Van den Berg & Klamt (1997).

5.2 Short history of concepts

5.2.1 Purity

Map purity is an indication of the degree of correspondence between what is indicated on the map and what is actually present in the field. It can be defined as the fraction or percentage of independently sampled sites that exactly match the legend description of the corresponding mapping unit. Purity can be determined either for the soil map as a whole, or for separate legend criteria. Determination of purity is simple, objective and quantifiable; but its interpretation is controversial.

The Soil Survey Manual of 1951 (Soil Survey Staff, 1951) states that *"a mapping unit contains up to about 15 percent of impurities"*. The 1993 edition (Soil Survey Division Staff, 1993) uses more nuances, by considering rather vaguely described "similar", "dissimilar", "very contrasting", "nonlimiting" and "limiting" soils. Indicative total amounts of inclusions (an often used euphemistic term for impurities) *"that are generally not exceeded"* are given in table 5.1.

Table 5.1 Types of inclusions in soil mapping units and indicative amounts that are generally not exceeded

Type of inclusion	description	indicative amount (%)
Similar soils:	soils that differ so little from the named soil in the map unit that there are no important differences in interpretations;	50 *
Dissimilar soils	soils that differ sufficiently from the named soil to affect major interpretations;	25
- nonlimiting	do not restrict the use of entire areas or impose limitations on the feasibility of management practices.	25
- limiting	significantly lower potential for use than the dominant component in the map unit or that affects the feasibility of meeting management needs	15
- very contrasting	soils with properties that are very contrasting with the named soil (not specifically defined);	10

*may be more if most of the remainder of the mapping unit consists of 2 or more similar soils.

It is inferred, but not clearly stated, that the named soil should normally cover at least 50% of the area.

Source: Soil Survey Division Staff (1993, p. 27-31 and p. 320)

The review of Beckett & Webster (1971) reports observed impurity values ranging from 4 % to 83 %, with a median of 50 % for soil series, but impurity estimates provided by Soil Survey reports are often in the 5 to 15 % range. According to Brown & Huddleston (1991) this contrast reflects *"perhaps some disinclination to report the truth"*. It seems more likely that impurities are underestimated because the method that is often used for their determination is biased. According to the Soil Survey Manual (Soil Survey Division Staff, 1993; p. 29): *"The actual amount of inclusions is estimated from observations made during the survey. Adjustments in mapping are made if appropriate."*

Marsman & de Gruijter (1984) and Burrough et al., (1971) have argued that the concept of purity has little meaning, because it can be manipulated by broadening or narrowing legend definitions. For example, stating that the soil of a mapping unit has a pH ranging between 1 and 14 will give 100 % purity, but 0 % information. Nevertheless, information on purity, in combination with other criteria, is thought to be helpful; not just for quantifying mapping errors, but rather to assess the balance between the level of generalisation in the legend of a map and real world complexity. Purity studied for individual legend criteria helps judging whether adopted class boundaries are appropriate, or whether legend criteria are impracticable because of large short-range variability.

5.2.2 Homogeneity of mapping units

A simple and powerful method to estimate the homogeneity of mapping units is by determining "within mapping unit variance" (e.g. de Gruijter & Marsman, 1985; Beckett & Webster, 1971; Webster & Oliver, 1990). It can be calculated for individual soil characteristics with a one-way analysis of variance. Multivariate methods provide more information, but are more difficult to interpret. Once the within mapping unit variance is known, third parties can use this information for error analysis.

Analysis of variance of soil characteristics within and between taxonomic units can be used, for example, to indicate the appropriateness of a soil classification system to separate land evaluation units. The smaller the "within-class variance" of relevant soil characteristics, the better the classification system can be used to "translate" soil classes to suitability classes.

Many soil scientists use the coefficient of variation (CV) to indicate homogeneity of mapping units (Beckett & Webster, 1971; Wilding & Drees, 1978). CV is defined as the standard deviation divided by the average value, usually expressed as percentage. This yields dimensionless values, so that results for different characteristics would be comparable. Interpretation is however obscure. For example, a mapping unit with average soil pH of 8 and standard deviation 2 would have a CV of 25 %. Is this comparable with a CV of 25 % for clay content of the same mapping unit with average clay content of 80 $g\,kg^{-1}$ and standard deviation of 20 $g\,kg^{-1}$?

Some soil characteristics tend to present more variability within mapping units than others. Wilding & Drees (1978) provide the following indicative ranges based on compiled information from published and unpublished sources:

- least variable properties (CV commonly < 15 %), e.g. colour hue and value, pH;
- moderately variable properties (CV commonly between 15 and 35 %), e.g. particle size separates (sand, clay, silt content), cation exchange capacity, base saturation;
- most variable properties (CV commonly > 35 %), e.g. soil colour chroma, exchangeable cations, organic matter content.

5.3 Materials and methods

The following strategy was used to accomplish the objectives:

- Soil data from auger samplings [395 sites on the 33 fields with sugarcane (Araras and Assis) or soybean/wheat rotation (Assis), as described in Chapter 3 and 4 were compared with soil maps.
- Map quality indices were determined: (1) Purity of mapping units for several legend criteria, (2) variance of soil characteristics within mapping units, (3) variance of soil characteristics within soil classification units.
- A detailed identification was done on 23 soil profiles from selected fields for comparison with soil maps and with the more general information from the auger sampling.

5.3.1 Studied soil maps

In the Araras region, the soil maps used for ground truthing, are the same as were used for selection of "homogeneous" sugarcane fields as described in Chapter 4. They are part of the 1 : 100 000 soil mapping programme for São Paulo State, carried out by the Pedology Section of the "Instituto Agronômico de Campinas" (IAC). The study fields belong to the sheets of Campinas (Oliveira et al, 1977); Araras (Oliveira et al, 1981) and São Carlos (Prado et al, 1981). In Assis, "homogeneous" sugarcane fields had been selected by using the 1: 50 000 map of Souza Dias (1985), and soybean/wheat fields by using personal information from local farmers and extension workers. Comparison between map information and ground truth in Assis was made with a final draft of the 1 : 100 000 soil map (Bognola et al., 1996), prepared under the responsibility of the Pedology section of IAC, which was supposed to be ready for publication, but corrections were made when data from the present study came available.

All soil maps that formed the basis for this study were elaborated according to the methodology related by Oliveira & Prado (1984), summarised as follows: Initially, main physiographic units are delimited, using topographic maps at scale 1 : 50 000 and aerial photographs at scale 1 : 60 000. Subsequently, observations are made along several transects covering complete topo-sequences in all physiographic units, in order to visualise distribution patterns of soils in the landscapes and to establish a preliminary legend. The next phase consists of a systematic soil survey, following a predetermined route, making inspections on auger samples, profile pits and road cuts; and carefully observing the general aspects of the landscape and the soil along road cuts when moving between consecutive sites. The final legend is established during this phase. The soil maps are drawn on top of topographic sheets, which are later reduced to the scale of publishing at 1 : 100 000. For each taxonomic unit, at least one profile is completely described and sampled for laboratory analysis. Approximately 30-35 % of the samples collected during the systematic soil survey are analysed in the laboratory (493 for the Araras sheet, no exact number is available for Assis). Statistics of results (average, variance, minimum, maximum) for each soil class are presented in the report that accompanies the maps.

Map legend criteria follow the concepts and terminology of soil classification in use in Brazil, as outlined for relevant soil units in table 2.1 (Chapter 2). According to the maps, all soils of the study fields are strongly weathered and - except those that are sandy textured throughout - have either a textural B horizon or a latosolic B horizon.

5.3.2 Field methods

Auger sampling procedures and methods for determining soil characteristics in the field at the 395 sites are described in Chapter 4.

The 23 sites for profile pits were selected after the auger sampling, in such a way that they (appeared to) represent the soil of the selected field. The sites were on land with slopes < 5 cm m^{-1}, because they were also used for studies on soil-water relations *in situ*, as described in Chapters 6 and 7. For the same reason the sites had to be accessible to lorries. Soil profiles were described according to the Guidelines for soil profile description (FAO,1977). Samples from each horizon were taken to the laboratory.

5.3.3 Laboratory methods

Laboratory methods are the same as those that were used for the elaboration of the studied soil maps. Technical staff in the same laboratories of *Instituto Agronômico de Campinas* (sections of Pedology and Soil Fertility and Plant Nutrition), did the analyses. Analysis methods for the auger sampling are described in Chapter 4. The following analyses were done additionally, on selected samples from B horizons of the soil profiles and a few auger samples of the 60-80 cm layer in each field: total Fe_2O_3, Al_2O_3, TiO_2, and SiO_2 (g kg^{-1}), by spectrophotometer after destruction with sulphuric acid and sodium hydroxide (according to Camargo et al., 1986).

5.3.4 Classification

The soil at each sampling site was classified according to the map legend criteria. An unambiguous classification of auger samplings was not always possible. The following simplifications were applied: (1) the 60-80cm layer was considered representative for the B horizon; (2) field records up to 100 cm depth and clay ratio between sampled depths [(clay content 0-20 cm layer) ÷ (clay content 60-80 cm layer)] were used to identify textural B horizons because clay skins cannot often be identified on auger samples; (3) only colour was used to separate classes at the second level because Fe_2O_3 and Al_2O_3 contents were measured on few samples only; (4) the diagnostic difference in colour between the A horizon and the horizon just above the weathered rock could not be checked in deep soils. Therefore colour comparisons were made between the 0-20 and 60-80cm layers. Note that, in practice, this criterion is usually not regarded in Brazilian soil surveys (J.B. de Oliveira, 2000, personal communication). No distinction was made between chernozemic and prominent A horizons.

5.3.5 Statistical analysis

Purity

Purity for separate legend criteria of the soil maps was calculated as the percentage of independent observations that match the legend criterion of interest. Total purity was calculated as the percentage of independent observations that match all legend criteria. The independent observations are the 395 auger samplings.

Note that these observations are independent in a sense that they were not used to elaborate the study maps, but, considering the results of Chapter 4, observations within fields are not spatially independent. On the 1 : 100 000 maps the study fields cover not more than a few cm^2, and the average distance between neighbouring observation sites of some 300 m is represented by only 3 mm on the maps. Sites in each field in Araras are mostly within the same mapping unit. This was generally not the case in Assis, were one map was used for field selection and another one for ground truthing.

For Araras, the legend printed on the map sheets specifies for all units of Red Yellow Latosols that trophic character is allic; but the accompanying report describes the concepts of these units as "allic or dystrophic". The latter description was used for purity analysis.

Comparison of purity results with indicative figures of the Soil Survey Manual as given in table 5.1, is ambiguous, since the terms similar, limiting and strongly contrasting are not objectively defined. They depend on the expectations of the user of the map. For this study, dissimilar limiting inclusions were marked by following the criteria of the Land Suitability study of Oliveira & van den Berg (1983, 1985) for the Araras sheet: soils with textural B horizon instead of Latosolic B (related to erosion hazard); soils with inferior trophic character in the B horizon than indicated (related to natural fertility and Al-toxicity) and soils with sandy instead of medium or clayey texture (related to water availability).

Analysis of variance

The SYSTAT (Systat Inc., 1985) package was used for one-way analysis of variance of soil characteristics within and between soil mapping units, and soil classification units for the observations of the overall sampling. Soil classification units were defined by application of the legend criteria of the soil maps (table 2.1) to the independent observations of the overall sampling.

Analysis of variance was done at three levels of generalisation (see table 2.1), both by mapping units as well as by soil classification units. Groupings with less than 5 occurrences were lumped together with the nearest grouping at the lowest possible level of generalisation. Results for the same terrain and soil characteristics as in Chapter 4 are reported: Elevation above mean sea level (ALT, m), slope percentage (SL, $cm\,m^{-1}$), Munsell colour hue and chroma; pH-KCl; sum of exchangeable bases (SB, $mmol_c\,kg^{-1}$); cation exchange capacity (CEC, $mmol_c\,kg^{-1}$); base saturation (V%, percentage of CEC), aluminium saturation (Al%,); organic carbon content (C, $g\,kg^{-1}$) and resin extractable P (P, $mg\,kg^{-1}$). SL, Al%, V% and P were log transformed prior to the analyses.

Pooled coefficients of variance (CV) were calculated for each characteristic as the square root of pooled within unit variance divided by the regional average; in order to compare homogeneity of mapping units with the indicative ranges of Wilding & Drees (1978), cited before.

Table 5.2 Purity analysis for Araras

Soil map units						number of discrepancies with field observations related to:							
hierarchical levels 1+2	A	TC	txt	total	conf	A±	TC+	TC-	C+	C-	B±	txt+	txt-
Quartzose Sands	-	-	s	21	15	-	-	-	-	-	2	6	-
Red Yellow Podzolics	m	d+a	c+m/c	15	3	1	1	-	0	-	12	0	0
Dusky Red Latosols	m	e	fc+c	35	12	8	-	12	-	11	0	-	1
Dusky Red Latosols	m	d	fc+c	1	1	0	0	0	-	0	0	-	0
Dark Red Latosols	M	a+d	c+fc	18	7	2	4	-	0	8	0	-	0
Dark Red Latosols	M	a+d	m_f	9	3	1	0	-	0	5	0	0	3
Red Yellow Latosols	w+m	a+d	m_s	11	1	3	0	-	0	-	0	0	10
Red Yellow Latosols	M	a+d	m_f	19	5	12	0	0	6	-	0	1	2
Red Yellow Latosols	P	a+d	m_f	16	10	3	1	-	4	-	1	0	0
Red Yellow Latosols	M	a+d	c	21	11	2	2	-	2	-	0	1	5
totals				166	68	32	8	12	12	24	15	8	21
totals (%)				100	41	19	5	7	7	14	9	5	13

Abbreviations soil map units:
A: type of A-horizon: w weak, m moderate, p prominent;
TC: trophic character: a allic, d dystrophic, e eutrophic;
txt: texture class: fc very fine clayey, c clayey, m medium, m_f fine medium, m_s sandy medium, s sandy.
+ : association, e.g. "a+d" is association of allic and distrophic soils;
/ : textural differentiation, e.g. "s/m" sandy A or E horizon and medium textured B horizon.

total: total number of observations; conf: Number of observations that match soil map.

Abbreviations discrepancies:
A±: Soil map does not match observations with respect to type of A horizon;
TC+ observed trophic character "better" than mapped; TC-: trophic character "worse" than mapped;
C+: observed soil colour redder than mapped; C-:colour yellower than mapped;
B±: Soil map does not match observations with respect to type of B horizon;
txt+: observed soil texture finer than mapped; txt-: texture coarser than mapped;
- : combination not relevant [e.g. trophic character cannot be better (TC+) than eutrophic].

5.4 Results

5.4.1 Purity of soil maps

In Araras, for 11 sites the collected information was insufficient to judge whether or not they corresponded to the map indications. Doubts were related to colour in 6 cases (dark red or dusky red), and to the presence or not of a textural B horizon in 5 cases. To avoid complications, 6 of these cases (3 related to colour and 3 to textural B horizon) were arbitrarily considered correctly mapped and the other 5 as impurities.

Average purity of the mapping units of the Araras region was estimated as 41% at the third level, 60% at the second level and 81% at the first level of generalisation. 23% (38

Table 5.3 Purity analysis for Assis

Soil map unit				number of discrepancies with field observations related with:										
hierarchical levels 1+2	A	TC	txt	total	conf	clac	A+	TC+	TC-	C+	C-	B±	txt+	txt-
Dark Red Podzolics	m	e	m/c +s/m	3	1	0	0	-	1	0	0	2	0	0
Red Yellow Podzolics, abruptic	m	e	s/m	8	2	0	0	-	5	0	-	4	0	0
Dusky Red Latosols	m	e	fc	59	51	2	2	-	2	-	2	0	-	2
Dusky Red Latosols	m	d	fc	38	9	0	0	29	0	-	0	0	-	0
Dusky Red Latosols	m	d+a	fc	19	10	0	0	9	-	-	1	1	-	1
Dusky Red Latosols +Dusky Red Earths	m	e	fc	11	8	0	0	-	3	-	0	-	-	0
Dusky Red Latosols +Dark Red Latosols	m	d	fc+c	5	1	0	0	3	0	-	0	0	-	1
Dark Red Latosols	m	a	m	27	17	0	5	5	-	0	0	0	0	1
Dark Red Latosols, int. with Podzolics	m	e	m	44	2	1	1	-	32	0	1	11	4	0
Dark Red Latosols, int. with Podzolics	m	d	m+ m/c	14	0	0	2	11	2	0	0	2	0	1
Red Yellow Latosols	m	a	m	1	0	0	0	1	-	1	-	0	0	0
totals				229	101	3	10	58	45	1	4	20	4	6
totals (%)				100	44	1	4	25	20	0	2	9	2	3

Abbreviations soil map units:
A: type of A-horizon: w weak, m moderate, p prominent;
TC: trophic character: a allic, d dystrophic, e eutrophic;
txt: texture class: fc very fine clayey, c clayey, m medium, s sandy.
+ : association, e.g. "a+d" is association of allic and distrophic soils;
/ : textural differentiation, e.g. "s/m" sandy A - and medium textured B - horizon.

total: total number of observations; conf: number of observations that match soil map.

Abbreviations discrepancies:
clac: observed clay activity higher than indicated by soil map;
A+: prominent- or chernozemic A horizon observed but moderate A mapped;
TC+ observed trophic character higher than mapped; TC-: trophic character lower than mapped;
C+: observed soil colour has redder hue or higher chroma than mapped;
C-: observed soil colour has yellower hue or lower chroma than mapped;
B±: *Soil map does not match observations with respect to type of B horizon;*
txt+: observed soil texture finer than mapped; txt-: texture coarser than mapped;
- : combination not relevant [e.g. trophic character cannot be better (TC+) than eutrophic].

cases) of the sampled sites did not match the description of any of the legend units that were considered by the map (for example eutric Dark Red Latosols). Table 5.2 presents purity/impurity estimates for mapping units in Araras at the third level of generalisation.

The most frequent sources of discrepancy are (1) colour of the B horizon, especially of soils mapped as Dark Red Latosols; (2) type of A horizon, which was often mapped as moderate

Table 5.4 Soil profiles in the Araras region typified according to map unit and ground truth

field nr. (profile)	Legend description of mapping unit	confirmed +/-	Comments/reasons of discrepancy
01 (1471)	Dusky Red Latosol, eutrophic or dystrophic, moderate A, very fine clayey	-	Textural B is present $Fe_2O_3 < 180$ g kg^{-1}
02 (1484)	Dusky Red Latosol, eutrophic or dystrophic, moderate A, very fine clayey	+	
04 (1480)	Deep Quartzose sands, moderate A	+	
05 (1479)	Red Yellow Latosol, allic or dystrophic, moderate A, sandy-medium texture	-	Texture is sandy; A horizon is prominent
06 (1470)	Red Yellow Latosol, allic or dystrophic, prominent A, fine-medium texture	-	$Al_2O_3/Fe_2O_3 < 3.14$
07 (1482)	Red Yellow Latosol, allic or dystrophic, prominent A, fine-medium texture	+	
08 (1481)	Dark Red Latosol, allic or dystrophic, moderate A, clayey texture	+	
10 (1477)	Red Yellow Latosol, allic or dystrophic, moderate A, fine-medium texture	-	A horizon is prominent; allic→dystrophic below 98 cm depth
11 (1469)	Red Yellow Latosol, allic or dystrophic, moderate A, clayey texture	+	
12 (1468)	Dusky Red Latosols, eutrophic, moderate A, very fine clayey texture	+	
13 (1478)	Dark Red Latosol, allic or dystrophic, moderate A, fine-medium texture	+	
14 (1483)	Dark Red Latosol, allic or dystrophic, moderate A, clayey texture	-	$Fe_2O_3 < 80$ g kg^{-1}; eutrophic below 95 cm

but found too thick and dark, especially in medium textured Red Yellow Latosols; and (3) type of B horizon of soils that were mapped as Red Yellow Podzolics.

For the Assis region, purity was 90% at the first level, 86% at the second and 44% at the third (unit) level of generalisation. Purity/impurity estimates for mapping units at the third level of generalisation are given in table 5.3. The dominant source of discrepancy in the Assis region was trophic character (eutrophic, dystrophic, allic). In 58 cases (25%) trophic character was "better", i.e. higher base saturation or lower Al saturation, than indicated on the map; in 45 cases (20%) it was worse. Note that the legend criteria are narrower for the map of the Assis region than for the Araras region, where most mapping units are associations with respect to the trophic character.

Table 5.5 Soil profiles in the Assis region typified according to map unit and ground truth

field nr. (profile)	Legend description of mapping unit	confirmed +/-	Comments/reasons of discrepancy
02 (1509)	Dusky Red Latosol, dystrophic or allic, moderate A, very fine clayey texture	+	
03 (1508)	Dusky Red Latosol, dystrophic, moderate A, very fine clayey texture	-	Trophic character eutrophic
04 (1512)	Dark Red Latosol, allic, moderate A, medium texture	+	
06 (1507)	Dusky Red Latosol, dystrophic, moderate A, very fine clayey texture	-	Trophic character allic (below 100 cm)
08 (1511)	Dark Red Latosol, allic, moderate A, medium texture	+	
11 (1510)	Dark Red Latosol, intergrade with Podsolic, eutrophic, moderate A, medium texture	-	Trophic character allic
21 (1504)	Dark Red Latosol, intergrade with Podsolic, dystrophic, moderate A, medium or medium/clayey texture	-	Clayey throughout; Trophic character eutrophic
24 (1505)	Dark Red Latosol, intergrade with Podsolic, eutrophic, moderate A, medium texture	+	
25 (1503)	Dark Red Latosol, intergrade with Podsolic, eutrophic, moderate A, medium texture	-	$Al_2O_3/Fe_2O_3 > 3.14$ Trophic character allic (below 70 cm)
26 (1506)	Dusky Red Latosol, eutrophic moderate A, very fine clayey texture	+	
28 (1502)	Dusky Red Latosol, eutrophic moderate A, very fine clayey texture	?	Trophic character dystrophic below 125 cm

The type of A horizon was apparently a much less important source of impurity in the Assis region than in the Araras region. According to the map, all soils in the Assis region are supposed to have a moderate A horizon. More than 50 % (118 cases) of the sampled A horizons of this region met the colour, thickness and organic matter requirements for chernozemic or prominent A's, but showed too little difference in colour with the underlying horizons.

Comparison of soil map indications with the 23 detailed soil profile descriptions is summarised in table 5.4 for the Araras region and in table 5.5 for the Assis region. Results confirm the principal causes of impurity. Two profiles from Araras and another two from Assis had a trophic character (class) at 60-80 cm depth which was different from that of underlying horizons, i.e. the 60-80 cm layer was not always representative for "the B horizon". In profile 28 (table 5.5), the trophic character changed below 125 cm. Whether or not this change is diagnostic was not formalised when the maps were elaborated. The "new" Brazilian system of soil classification, (EMBRAPA, 1999) uses the major part of the upper 100 cm of the B horizon (including transitional BA) as a criterion, which would classify this soil as eutrophic.

Application of the criteria of the Land Suitability study of Oliveira & van den Berg (1983, 1985) for the Araras sheet, would give 25 cases (15%) of dissimilar limiting impurities in Araras and 48 cases (21 %) in Assis. 17 cases in Assis (7%) were allic where eutrophic was indicated.

5.4.2 Heterogeneity of soil mapping- and classification - units

Araras

Table 5.6 presents results of the analysis of variance by soil mapping unit and by taxonomic soil unit for the samples of the Araras region. The soil mapping units explained much of the variance in elevation, clay content, CEC and aluminium saturation of the 60-80 cm sample. For most other soil characteristics, especially of the 0-20 cm layer, the variance accounted for was rather small. Note that soil mapping units generally explained more variance than classification units. Pooled CV's were smaller than the indicative ranges of Wilding & Drees (1978) for colour chroma and organic carbon content of the 0-20 cm layer. CV's compared well with the indicative ranges for clay content, pH, sum of exchangeable bases, cation exchange capacity and organic carbon content of the 60-80 cm layer. The apparently low CV's of base saturation refer to log transformed values. CV's for the original data are some 40 %, i.e. more than the indicative range. CV's for Hue are large, but the method to transform Munsell Hues to numeric values may not have been the same as used by Wilding & Drees (1978).

Assis

Results of the analysis of variance by soil mapping unit and by taxonomic soil class for the samples of the Assis region are presented in table 5.7. The analysis of variance by field (combining fields with soybeans and sugarcane) is also included to facilitate comparison.

The variance accounted for by mapping units was not very much smaller than the variance accounted for by fields for most characteristics of the 60-80 cm layer. For the 0-20 cm layer, much of the variance in clay content, SB, C and CEC was accounted for by the map, but little variance was explained for pH, V% and Al%. On the whole, classification units explained as much variance as mapping units. For colour chroma, clay content and organic carbon content of the 0-20 cm layer, CV's are small in comparison with the indicative ranges of Wilding & Drees (1978). CV's compared well with their indicative ranges for the other characteristics. CV for "untransformed" base saturation percentage was in the range 25 to 35%.

Table 5.6 Variance by soil map and soil taxon for 166 sites in the Araras region

Terrain and 0 – 20 cm			Colour			pH						
	ALT	SL	Hue	Chr	Clay	KCl	SB	CEC	Al	V	C	P
	m	$cm\,m^{-1}$			$g\,kg^{-1}$		$mmol_c\,kg^{-1}$		%	%	$g\,kg^{-1}$	$mg\,kg^{-1}$
% of variance accounted for by soil map:												
3 map "orders"	66	15"	3	7	33	9	14	37	2"	0"	22	8"
5 map "classes"	66	15"	33	14	66	9	30	47	6"	8"	25	15"
10 map "units"	79	28"	33	15	84	17	44	62	12"	14"	40	39"
pooled variance within map units												
variance	394	.59"	73	.62	6.3'	.27	311	328	2.7"	.21"	16	.52"
CV (%)	3	55"	24	25	23	11	53	28	103"	12"	33	69"
% of variance accounted for by soil taxons classified according to map legend criteria												
3 soil "orders"	41	12"	1	0	41	1	13	33	0"	0"	26	10"
5 soil "classes"	49	12"	62	1	60	2	28	46	5"	4"	40	24"
13 soil "units"	53	10"	62	14	78	8	47	62	10"	15"	51	25"
pooled variance within taxonomic units												
variance	886	.74"	42	.63	8.5'	.30	294	329	2.8"	.21"	13	.65"
CV (%)	4	62"	18	26	26	12	52	28	105"	12"	30	78"
60-80 cm												
% of variance accounted for by soil map:												
3 map "orders"	-	-	3	3	33	14	7	29	9"	1"	10	0"
5 map "classes"	-	-	27	7	65	37	28	37	46"	27"	17	12"
10 map "units"	-	-	31	13	84	49	40	50	59"	42"	27	12"
pooled variance within map units												
variance	-	-	71	1.7	7.2'	.13	170	265	1.4"	.19"	8	.45"
CV (%)	-	-	24	27	21	8	72	35	46"	13"	57	39"
% of variance accounted for by soil taxons classified according to map legend criteria												
3 soil "orders"	-	-	1	1	39	7	10	21	8"	8"	16	1"
5 soil "classes"	-	-	62	29	57	27	31	32	36"	22"	30	17"
13 soil "units"	-	-	63	34	76	33	50	44	48"	42"	33	15"
pooled variance within taxonomic units												
variance	-	-	38	1.3	10.8'	.16	142	293	1.7"	.19"	7.5	.43"
CV (%)	-	-	18	23	26	9	66	36	51"	13"	55	39"

' multiply values by 10^3

" analysis performed after transformation to natural logarithm

ALT = elevation above mean sea level. SL = slope. SB = sum of exchangeable bases. CEC = cation exchange capacity. Al = aluminium saturation percentage ($100\,Al^{3+}/(SB+Al^{3+})$). V = base saturation percentage (100 SB/CEC). C = organic carbon content. P = resin extractable phosphorous.

5.5 Discussion

5.5.1 General aspects

For most soil variables, soil mapping units explained as much variance as classification units; often even more. This is quite remarkable when considering the rather high impurities of the maps for several variables, notably base saturation and Al saturation in Assis. This may reflect bias on the part of the surveyors, who map natural soil boundaries in the field, which are correlated afterwards with taxonomic boundaries with which they do not really correspond. Preference for road cuts for the selection of "representative profiles" may contribute to systematic errors.

Table 5.7 Variance by soil map and soil taxon for 229 sites in the Assis region

Terrain and 0 – 20 cm	ALT	SL	Colour Hue	Chr	clay	pH KCl	SB	CEC	Al	V	C	P
	m	$cm.m^{-1}$			$g\ kg^{-1}$		$mmol_c\ kg^{-1}$		%	%	$g\ kg^{-1}$	$mg\ kg^{-1}$
general statistics												
Total variance	4589	8	12	.16	63.4'	.33	1178	1617	115	342	38	493
Field variance	213	4	7	.10	3.4'	.19	521	446	87	200	9	281
%Var. explained	95	46	41	38	95	43	56	72	24	42	77	43
log transformed data												
Total Variance	-	.84	.012	.017	.58	.012	.60	.37	1.8	.12	.32	1.03
field variance	-	.47	.007	.011	.04	.007	.22	.06	1.2	.08	.06	.40
%Var. explained	-	44	42	35	93	42	64	83	37	34	81	61
% of variance accounted for by soil map:												
2 map "orders"	0	2"	0	0	8	0	5	7	3"	0"	8	4"
3 map "classes"	4	16"	15	4	90	2	39	61	4"	0"	69	8"
9 map "units"	30	19"	15	18	95	7	48	69	15"	9"	73	36"
pooled variance within map units												
variance	3198	.68"	10	.13	3.3'	.31	617	507	1.6"	.11"	10	.66
CV (%)	13	76"	11	11	13	11	51	32	150"	8"	26	33
% of variance accounted for by soil taxons classified according to map legend criteria												
2 soil "orders"	0	1"	8	5	12	1	3	7	0"	2"	7	1"
3 soil "classes"	5	11"	20	8	89	1	31	53	2"	1"	63	8"
7 soil "units"	16	12"	19	13	94	14	43	62	21"	19"	68	13"
pooled variance within taxonomic units												
variance	3869	.76"	9.4	.14	3.6'	.28	669	618	1.4"	.10"	12	.90"
CV (%)	14	80"	10	12	14	10	53	35	145"	8"	28	39"
60-80 cm												
general statistics												
Total variance	-	-	6	.30	60.1'	.49	554	538	753	667	.11	17
Field variance	-	-	4	.18	2.1'	.18	205	144	208	273	.05	15
%Var. explained	-	-	30	41	97	63	63	73	72	59	51	11
log transformed data												
Total variance	-	-	.005	.017	.38	.021	1.29	.271	3.5	.54	28	.40
Field variance	-	-	.004	.009	.02	.007	.29	.049	1.1	.19	9	.30
%Var. explained	-	-	32	44	96	65	78	82	67	65	67	25
% of variance accounted for by soil map:												
2 map "orders"	-	-	0	1	8	4	3	7	3"	0"	4	1"
3 map "classes"	-	-	12	17	89	45	45	56	46"	34"	41	12"
9 map "units"	-	-	13	20	96	56	53	62	60"	56"	43	19"
pooled variance within map units												
Pooled unit var	-	-	5.1	.24	2.5'	.21	261	204	1.4"	.24"	6	.33"
Pooled CV (%)	-	-	7	12	10	10	55	30	64"	13"	42	54"
% of variance accounted for by soil taxons, classified according to map legend criteria												
2 soil "orders"	-	-	7	4	6	1	1	3	1"	0"	5	0"
3 soil "classes"	-	-	16	22	86	39	33	44	39"	29"	43	11"
7 soil "units"	-	-	15	22	93	67	61	58	73"	70"	43	12"
pooled variance within taxonomic units												
pooled unit var	-	-	5.0	.24	4.1'	.16	217	228	.93"	.17"	6	.36"
Pooled CV (%)	-	-	7	12	12	8	50	31	52"	11"	42	56"

' multiply values by 10^3

" analysis performed after transformation to natural logarithm

ALT = elevation above mean sea level. SL = slope. SB = sum of exchangeable bases. CEC = cation exchange capacity. *m* = aluminium saturation percentage (100 $Al^{3+}/(SB+Al^{3+})$). V = base saturation percentage (100 SB/CEC). C = orgnic carbon content. P = resin extractable phosphorous.

Broadening definitions increases the purity of a map. The more general use of associations in the legend of the Araras map explains the better purity for the trophic character in the Araras region in comparison with the Assis region (compare tables 5.2 and 5.3). Both maps were remarkably successful in separating and identifying areas with homogeneous texture. The map (legend) of the Assis region could possibly be more refined with respect to this aspect, as was done for Araras by separating sandy-medium and fine-medium textured soils.

In Assis, for most variables, the percentage of variance accounted for by mapping increased strongly by refining the level of generalisation from the first ("order") to the second ("class") and just slightly from the second to the third ("unit"). This is remarkable because soils are grouped with respect to the trophic character and texture at the third level. Analysis of variance for soil taxons shows larger differences between the second and third levels. This seems to be related with the relatively simple geologic structure of this region. Mapping units were distinguished according to broad landforms (related with parent material), which show strong correlation with characteristics used for separating soil groupings at the second level (colour and related sesquioxide contents) and at the third level (textural class, trophic character). To reveal soil patterns within broad landforms seems almost impossible without intensive sampling.

5.5.2 Relation with spatial variability

Comparisons of these results with the results of Chapter 4 is possible since the same data were used and total variances mentioned in tables 4.1, 4.2 and 4.3 also apply to this Chapter. Variables with high within-field variance also have high within-soil-unit and -map-unit variance and *vice versa*. Within soil/map unit variance is generally larger than within field variance and semivariance at 1 km lag, especially for easily modified soil characteristics. This suggests that regular sampling at 1 km grids could result in isorithmic-maps with a better quality than the studied maps. However, at considerable extra cost, since this would require 2805 sampling sites for a sheet covering 55x51 km^2, whereas for the Araras map only 493 sites were sampled for laboratory analysis.

5.5.3 Possibilities for improvement of map quality

Some trends appeared in the purity analysis that could be used to the advantage of surveyors in future mappings, as an alternative to more intensive sampling:

- All samples of the 60-80 cm layer from Dusky Red Latosols (as observed) in Araras and Assis had very fine clayey texture.
- Of all Dark Red Latosols, only two had very fine clayey texture.
- Of all observed clayey and very fine clayey Dusky Red Latosols and Dark Red Latosols only 3 were allic (one of which was profile 02 in Table 5.5).
- Of all clayey and very fine clayey soils in Araras and Assis, only 12 were allic. 10 of these had been mapped as Red-Yellow Podzolics and were situated in field 3 in Araras.

Descriptions of mapping units could be more precise and map purity could be improved if these considerations prove to be of general application to regions with similar soil forming conditions (geology, climate, relief, vegetation/land use). It was shown that the maps were very successful with respect to the correct identification of soil texture classes. The combinations [Dusky Red Latosol + clayey] and [allic + clayey or very fine clayey] could simply be ignored in such regions. This needs validation, because the 395 augered sites were clustered in fields. Nevertheless, even if we consider fields rather than sites as independent observations; having 17 fields with predominantly clayey and very fine clayey textured soils (7 in Araras, 10 in Assis) of which only 1 has predominantly allic soils, gives a strong indication that the maps could be improved, e.g. by stating that strongly weathered clayey soils in the regions are usually not allic. Note that the trophic character of the subsurface horizon is of great importance for both high input and low input agriculture.

Another tool for soil mapping is the use of vegetation as a soil indicator. For example, Oliveira et al. (1981) stated that cerrado vegetation is strongly related with allic and dystrophic soils, whereas soils under forest are either dystrophic or eutrophic. Oliveira (1995) used the distribution of "bacuri" palms [*Scheelea phalerata* (Mart.) Burret], for the delimitation of eutrophic Dusky Red Latosols. Farmers do not cut these trees on their fields, because they form an evidence of good, valuable soil. As to our knowledge, no investigations have been undertaken so far, to quantify these relations.

It was shown in Chapter 4 that the major part of soil variability within distances smaller than say 1000 m, is present within 50 m or even less. This short range variability could be removed by bulk sampling, by which each bulked sample is composed of samples from a small area (e.g. 10 x 10 m^2). This would make long range patterns and correlations as suggested above more evident, and may possibly reveal medium range pedological structures.

As shown above, the studied soil maps are as good in separating land units as the classification system on which their legend is based, but taxonomic legend descriptions of mapping units do not correspond well with ground truth. For future mapping it may be wise to base map legends on what is actually being mapped rather than on the desire to make comprehensive and consistent legends, based on taxonomic classes, with mutually exclusive definitions.

5.5.4 Consequences for Land Evaluation

It is obvious that the obtained results have important implications for using soil maps for land evaluation. The maps were very successful in separating and identifying areas with homogeneous soil texture, which is of great importance for land use. Problems arise with the land quality “soil fertility” or “nutrient availability”, as reflected by the trophic character (Al%, V%), resin extractable P and organic C. Maps of both regions have a large within-unit variance for Al%, V% and P, especially in the surface layer. The map of the Assis region has many impurities for the trophic character, whereas map units in the Araras region are very broadly described. The type of A horizon could be an important aspect in land evaluation, but the criteria for identification are not uniformly applied. It would be justified to exclude the colour differentiation criterion in deep soils, which is already common practice in Brazilian surveys, because it is impracticable and probably disturbs correlation with soil suitability. Paradoxically, more than half of the studied soils in Assis have A-horizons with all aspects of prominent or chernozemic, except colour differentiation, but all soils had been mapped as having moderate A's. A check of field records of that survey suggests that not much attention had been paid to this aspect.

It is quite possible that diagnostic properties of surface horizons were changed by management: Liming may have increased base saturation; subsoiling may have increased the thickness of the A horizon and addition of sugarcane wastes may have increased the organic matter content (Camargo et al, 1983). Hence, A-horizons that were originally moderate may have been transformed to prominent or chernozemic. Data presented by Oliveira (1995) and Lepsch et al. (1994) show that high-input agriculture may also affect subsurface horizons.

These considerations imply that "nutrient availability" cannot be inferred from soil maps alone. Additionally, one should use records of past management of individual fields to assess this land quality. In regions that have never been used for agriculture soil maps may reflect the spatial variation of chemical soil characteristics better.

If crop yield models are used for land evaluation, it is clear that feeding the models with soil unit legends and data from "representative profiles" alone is not sensible. If model outcomes are approximately linearly related to soil variables, and if the variance is small, then "representative soil data" could be obtained by averaging. In other cases it is preferable to run the model many times over the observed ranges of attributes from numerous observations, after which an average result can be calculated and errors estimated.

5.6 Conclusions

1. Semi-detailed (scale 1 : 100 000) soil maps of the study regions contain useful information for regional land development; especially those involving agriculture with advanced management. The land quality "nutrient availability" cannot be inferred from soil maps alone, because it seems very much influenced by past management, and analysed maps either give very crude indications or have high impurities with respect to the trophic character.

2. Analysis of map purity and analysis of variance by mapping unit, when used in isolation, have limited value for the assessment of map quality. Together, they are very useful complementary techniques.

3. Soil surveyors should be more concerned about matching legends with what is actually being mapped rather than with taxonomic classification systems.

4. Feeding crop yield models with soil unit legends and data from "representative profiles" alone is not sensible.

5. Possibilities to improve quality of choropleth maps by bulk sampling and regional correlation between easily mappable land characteristics and difficult soil properties need to be explored.

PART III

SOIL WATER RELATIONS

6. AVAILABLE WATER CAPACITY

6.1 Introduction

An important aspect of agricultural land use systems is water sufficiency, i.e. the degree to which crop water requirements are satisfied. Annual rainfall in the study regions is sufficient to cover these requirements (potential evapotranspiration), but rainfall is not evenly distributed over the year, especially in the Araras and Assis regions (see chapter 3). Apart from seasonal variations, dry spells during the rainy summer months, so-called veranicos, are hold responsible for major yield differences between years and on different soil types. Crop water requirements during dry periods are (partly) met by withdrawal of temporary stored water from the soil. For quantified assessments of water (in)sufficiency and its impacts on crop growth and yields, e.g. with crop growth models as discussed in chapter 1, it is necessary to keep track of each component of the water balance. This chapter is concerned with the capacity of soils to store water available to plants, often indicated by the term available water capacity (AWC).

AWC is defined as the amount of water retained in the rooted soil between field capacity (FC) and permanent wilting point (PWP). Data on FC, PWP and consequently AWC are scarcely available. Therefore, so-called (pedo)transfer functions – or rules – have been proposed to generate AWC data on the basis of routinely measured soil properties (e.g. Batjes, 1996).

Some authors contend that the use of such simplified concepts, including AWC itself, may lead to unacceptable errors in the assessment of water availability on strongly weathered soils (see Reichardt, 1988; Wolf, 1975). However, alternative methods require soil water monitoring in the field and are hampered by time-consuming analyses and the lack of adequate equipment. It is therefore worthwhile to test the AWC, FC and PWP concepts and their relations with routinely measured soil properties.

The objectives of the study presented in this chapter are (1) to explore the adequacy of the concepts of field capacity (FC), permanent wilting point (PWP) and available water capacity (AWC) and (2) to identify relationships between these soil water characteristics and routinely measured soil properties, with respect to 30 strongly weathered soils of the three study regions in South East and Southern Brazil.

6.2 Background

Water discharge by an initially saturated, freely draining soil will virtually cease within a few days, even though a considerable amount of water remains in the soil. The water content (θ) of the soil at which the soil-water system appears to have reached equilibrium became known as the field capacity (FC) (Veihmeier & Hendrickson, 1931). FC is often considered as the upper limit of the soil water fraction that is available to crops. For deep draining soils, FC is often set to the soil water content at a soil water potential of some -33 kPa. Data presented by Wolf (1975), Freire (1979), Reichardt (1988) and Cadima (1984) in Southern America and by Pidgeon (1972) and Mensah Bonsu & Lal (1975; quoted by Lal, 1981) in Africa, suggest that a matric potential value of -33 kPa, is too low to represent FC of strongly weathered soils. Wolf (1975) and Reichardt (1988) stressed that the concept of FC must be treated with caution; they measured downward water flow even after several weeks of drainage. In spite of the small flow rates, such fluxes can be important, e.g. for leaching of nutrients. They proposed to substitute the water content at a matric potential of -6 to -10 kPa for FC, for calculating irrigation needs.

The soil water content associated with permanent wilting of a crop, the permanent wilting point (PWP) is often set to the water retained at a matric potential of ψ = -1.5 MPa. The exact value of ψ at which permanent wilting occurs seems not very important for strongly weathered soils because $d(\theta)/d(\psi)$ becomes very small below water potentials of about -0.4 MPa (e.g. Sharma & Uehara, 1968). The few studies that were dedicated to plant wilting on strongly weathered soils seem to confirm this notion. Pidgeon (1972) reported water contents that were within 0.005 $g\,g^{-1}$ of the water retained at -1.5 MPa in strongly weathered soils under wilted vegetation (without specifying the vegetation) in Uganda. In São Paulo State (Brazil), De Souza Dias (personal communication) analysed soils under sugarcane that showed clear symptoms of water shortage. Soil water contents in the 20 to 50 cm depth layer varied by no more than 1 g g-1 from the contents at -1.5 MPa. However, water contents were considerably less in the upper 20 cm and more in the 80 to 100 cm layer. The small water contents of the upper 20 cm layer might be explained by evaporation losses, whereas the water content of the 80-100 cm layer reflects less effective rooting at that depth and (consequent) preferential uptake from surface layers (Gardner, 1991; Cabelguenne & Debaeke, 1998). Few data are available on soil water retention at matric potentials less than (i.e. more negative than) -1.5 MPa. Clay soils may contain as much as 0.3 $g\,g^{-1}$ at -1.5 MPa. Sharma & Uehara (1968) examined two strongly weathered soils and found that the bulk of the water present at -1.5 MPa was still retained at -10 MPa. This water is certainly not available to crops.

FC and PWP are dynamic features, resulting from interactions between soil, crop and atmosphere. Nevertheless, they are generally presented as if they were constant soil properties. This simplification also affects the definition of the available water capacity (AWC), which is the water retained between FC and PWP. Reference books generally state that AWC of strongly weathered soils is 'low' (e.g. ISSS Working Group RB, 1998b). Indicative values of 0.10 $cm^3\,cm^{-3}$ or less are often mentioned (Sanchez, 1976; Baver, 1972; Lal, 1979a). This notion was not confirmed by Van den Berg et al. (1997), who examined a world-wide set of data on strongly weathered soils. Average soil water retained between -10kPa and -1.5MPa was 0.127 $cm^3\,cm^{-3}$. This value is similar to the average value of field determined potential extractable soil water found by Ratliff et al. (1983), for soils of the United States of America.

Table 6.1 Regression equations describing soil-water relationships[1] as a function of easily measured soil characteristics[2] for mainly strongly weathered soils. Source: Berg et al (1997), with modifications

Source	Regression equation	r^2	Remarks
Soil Survey Staff, 1975	$w_{-1.5MPa} = 0.4\,Clay$	-	Soil Taxonomy used inverse of this equation to estimate clay content of oxic horizons.
Soil Survey Staff, 1990	$w_{-1.5MPa} = 1/3\,Clay$	-	Revision of Soil Survey Staff (1975)
Soil Survey Staff, 1992	$w_{-1.5MPa} = 1/3\,Clay + C$	-	Revision of Soil Survey Staff (1990)
Wambeke, 1974	$w_{-1.5MPa} = 0.23\,Clay + 0.10$	0.42	Ferralic horizons.
Lal, 1979b, 1981	$w_{-1.5MPa} = 0.48\,Clay + 0.045$ $w_{-33kPa} = 4.42\,C + 0.093$ $w_{-10kPa-1.5MPa} = 2.35\,C + 0.083$	0.59 0.46 0.40	Nigeria. Includes some hydromorphic soils and soils with high-activity clay.
Aina & Periaswamy, 1985	$\theta_{-1.5MPa} = 0.31 Clay + 0.021$ $\theta_{-33kPa} = 0.55\,(Clay+Silt)^{3)} - 0.13\,Sand{*}BD + 0.129$ $\theta_{-33kPa-1.6MPa} = 3\,(Clay{*}Silt) - 0.0878\,BD + 0.140$	0.93 0.90 0.83	Nigeria, mostly Ultisols and Alfisols with low-activity clays.
Pidgeon, 1972	$w_{-1.5MPa} = 0.36\,(Clay+Silt^{4)})^{3)} + 0.020$ $w_{-1.5MPa} = 0.19\,Silt^{4)} + 0.39\,Clay + 1.8\,C - 0.042$ $w_{FC} = 0.25\,(Clay+Silt^{4)})^{3)} + 0.112$ $w_{FC} = 0.16\,Silt^{4)} + 0.30\,Clay + 3.0\,C + 0.074$ $\theta_{FC-1.5MPa} = -0.184\,(Clay+Silt^{4)})^{3)} + 1.62\,C + 0.185$ $\theta_{FC-1.5MPa} = -0.200\,Clay + 0.71\,C + 0.185$	0.94 0.98 0.74 0.93 0.70 0.73	Uganda, soils with kaolinite as dominant clay mineral.
Dijkerman, 1988	$w_{-1.5MPa} = 0.39\,Clay + 0.007$ $w_{-33kPa} = 0.35\,(Clay+Silt)^{3)} + 0.020$	0.92 0.88	Sierra Leone. Mostly Ultisols. Includes some hydromorphic soils.
Karlsson, 1982	$\theta_{-1.5MPa} = 0.50\,Clay + 0.051$ $w_{-1.5MPa} = 0.36\,Clay + 0.036$ (assuming average BD = 1.5)	0.83 -	Tanzania. Includes some soils with high-activity clays.
Arruda et al., 1987	$w_{-1.5MPa} = 0.27\,(Clay+Silt^{4)}) + 0.011$ $w_{-33kPa} = 0.29\,(Clay+Silt^{4)}) + 0.099$	0.90 0.78	Brazil, São Paulo State. Well drained, mostly strongly weathered soils.
Tomasella & Hodnett, 1998	$\theta_{-10kPa} = 0.321 Clay + 0.543\,Silt + 0.098$ $\theta_{-33kPa} = 0.404\,Clay + 0.426\,Silt + 0.040$ $\theta_{-1.5MPa} = 0.396\,Clay + 0.150\,Silt + 0.009$	0.84 0.78 0.79	Brazilian Amazonia, mostly well drained strongly weathered soils.
Berg et al., 1997	$\theta_{-1.5MPa} = 0.28\,Clay + 0.064$ $\theta_{-1.5MPa} = 0.33\,Clay{*}BD + 0.104\,Silt{*}BD$ $\theta_{-10kPa} = 0.39\,Clay + 0.14$ $\theta_{-10kPa} = 0.35\,Clay + 0.21 Silt + 1.8\,C + 0.109$ $\theta_{-10kPa-1.5MPa} = -0.132\,BD + 0.282$ $\theta_{-10kPa-1.5MPa} = -0.11 Clay + 9.0\,10^{-4}\,SS - 0.105\,BD + 0.249$ $\theta_{-10kPa-1.5MPa} = 0.093\,Clay + 0.077$	0.70 0.83 0.76 0.86 0.38 0.48 0.21	Strongly weathered soils from several countries in S. America, Africa and Asia.

1) w = water content as mass ratio ($g\,g^{-1}$); θ = volumetric water content ($cm^3\,cm^{-3}$). The relationship is: $\theta = w \times BD/1.0$.
2) Contents of clay (< 2 µm), silt (2-50 µm), sand (> 50 µm), and C (organic carbon) as mass ratio ($g\,g^{-1}$); Bulk density (BD) in $g\,cm^{-3}$; Specific surface area (SS) in $m^2\,g^{-1}$.
3) Equation was originally written in terms of mass % of sand.
4) Silt in these equations was defined as fraction 2-20 µm.

Van den Berg et al. (1997) also examined published relations for strongly weathered soils that connect approaches to PWP, FC and AWC with routinely measured soil characteristics (e.g. texture, organic C content). These relations, together with some more recent findings, are given in table 6.1. PWP relations are relatively consistent. This is less so for estimates of FC, whereas representations of AWC suggested by different authors seem sometimes even contradictory. Possible reasons for inconsistencies among these studies are that (1) different methods were used to determine the values of dependent and independent variables of the regression equations and (2) most studies included some non-strongly-weathered soils, with different physical behaviour, e.g. Fluvisols, Vertisols. In extreme cases, a few outliers can have considerable effect on regression parameters.

The definition of AWC, i.e. FC-PWP, is conceptually weak. A discussion in a broader perspective is given in chapter 8. Nonetheless, the AWC may work in practical situations: if the water retention aspects of water availability outweigh the aspects related to root distribution, atmospheric demand and crop characteristics, or if these aspects can be considered independently. The findings discussed above suggest that field capacity is the most critical soil related aspect of AWC.

6.3 Materials and methods

Data from 126 layers of the 30 soil profiles in the three study regions were used for this study. The soil profiles from the Araras and Assis regions are the same as discussed in chapter 5 on map quality (tables 5.4 and 5.5). One soil profile was analysed in each study field in the Passo Fundo region. These are the same as discussed by Van den Berg & Klamt (1997).

Bunded wall square plots of 5x5 m were laid out with sets of 5 tensiometers (with mercury manometers) installed to depths of 15, 45, 75, 105 and 135 cm in the centres of the plots (two tensiometers were installed at each depth in the Passo Fundo region). Water was applied until the tensiometers, and the quantity of water applied, indicated that the soil had become saturated to a depth of 135 cm. Complete saturation could not be achieved in all cases. Excess water was removed from the surface by opening the bunds. The surface of the plots was covered with plastic foil, which in turn was covered with straw, soil material and/or newspapers, to protect it from the sun. In most cases some 15 m^3 of water had to be applied to the 5x5 m plots. The time until field saturation at 135 cm depth was usually about 5 hours.

To test the field capacity concept, matric potentials (ψ) were determined at least twice: after two days of free drainage (ψ_{2d}) and after five days of drainage (ψ_{5d}). Gravimetric determinations of field soil water content could only be done in few cases, on augered samples. These samples were immediately put in metal cans, which were sealed and taken to the laboratory for weighing and drying at 105°C. After each drainage experiment a profile pit was made for soil description and sampling.

Soil water retention in relation to matric potential was determined in the laboratory, at 0, -0.5, -2.0, -6.0, -10, -30, -50, -100, -200, -800 and -1500 kPa for the soils from Assis and Passo Fundo and at 0, -2.0, -6.0, -10, -30, -70, -100, -500 and -800 kPa for the soils from Araras. Water retention in the wet range ($\psi > -200$ kPa) was determined on undisturbed core samples of 100 cm^3, as described by Topp & Zebchuck (1979). For water potentials ≤ -200 kPa, the method of Richards (1965) was used with crushed samples. The undisturbed samples were also used to determine bulk density. The analyses were done at the Irrigation and Drainage Section of IAC (Campinas, SP). Average values of three replicates were used as representative for each sampled layer.

Four indications for the soil water content at field capacity were examined:

(i) the soil water content after 2 days of free drainage (θ_{2d}, $cm^{-3}\,cm^{-3}$);
(ii) the soil water content after 5 days of free drainage (θ_{5d}, $cm^{-3}\,cm^{-3}$);
(iii) the water retained at -10 kPa matric potential (θ_{-10kPa}, $cm^{-3}\,cm^{-3}$);
(iv) the water retained at -30 kPa matric potential (w_{-30kPa}, $g\,g^{-1}$)

θ_{2d} and θ_{5d} were calculated by loglinear interpolation between water retention data nearest to ψ_{2d} and ψ_{5d}. θ_{-10kPa} and w_{-30kPa} were determined on core samples. w_{-30kPa} is expressed on a weight basis, just for comparison with published data of table 6.1.

Permanent wilting point was assumed to correspond with the equilibrium soil water content at -1.5 MPa matric potential, $\theta_{-1.5MPa}$ ($cm\,cm^{-3}$), and $w_{-1.5MPa}$ ($g\,g^{-1}$) . The -1.5 MPa point was not determined in the Araras region, so $\theta_{-1.5MPa}$ was approximated as the water content at -0.8 MPa minus 0.004 $cm\,cm^{-3}$. This estimate is based on data from Passo Fundo and Assis.

Estimates of available water capacity ($\theta_{2d-1.5MPa}$, $\theta_{5d-1.5MPa}$ and $\theta_{10kPa-1.5MPa}$) were calculated by subtracting $\theta_{-1.5MPa}$ from the water contents θ_{2d}, θ_{5d} and θ_{-10kPa} respectively.

Soil properties that were correlated with the water retention data, were analysed with the routine methods of the Pedology Section of IAC (Camargo et al., 1986): bulk density (BD, $g\,cm^{-3}$), and contents of total clay, silt, coarse sand, organic C, water-dispersible clay, total Fe_2O_3 and total Al_2O_3, all in $g\,g^{-1}$.

Multiple regression was used to identify correlations between water retention data and other soil properties. Only variables that were significant at the 1% confidence level were admitted to the multiple regression analysis.

6.4 Results and discussion

6.4.1 Field water contents vs. laboratory data

Figure 6.1 compares the $\theta(\psi)$ data obtained by determination of gravimetric water content on auger samples and tensiometer readings in the field with θ data at the same value of ψ, obtained from soil water retention curves determined from laboratory data. Field water contents were generally 0.02 to 0.04 $cm^3 cm^{-3}$ less than laboratory water contents at corresponding ψ. This discrepancy was also observed by Uehara & Gilman (1981) and by Freire (1979). They attribute the lower field water contents to the presence of entrapped air in the field situation, which would be absent in the laboratory situation because of the long time of saturation. Pidgeon (1972) adds that very dry soil material may become hydrophobic (see also Ritsema, 1999). The latter seems improbable in the present study, because (1) the soils were not very dry before the start of the experiments (ψ always > -70 kPa); (2) tensiometer readings during infiltration suggested uniform downward movement of the wetting front and (3) the soil samples were taken 7 days or more after saturation. Possible errors in the gravimetric data on auger samples are water loss due to squeezing of wet auger samples and drying during sample treatment. The influence of these factors on soil water data has not been quantified.

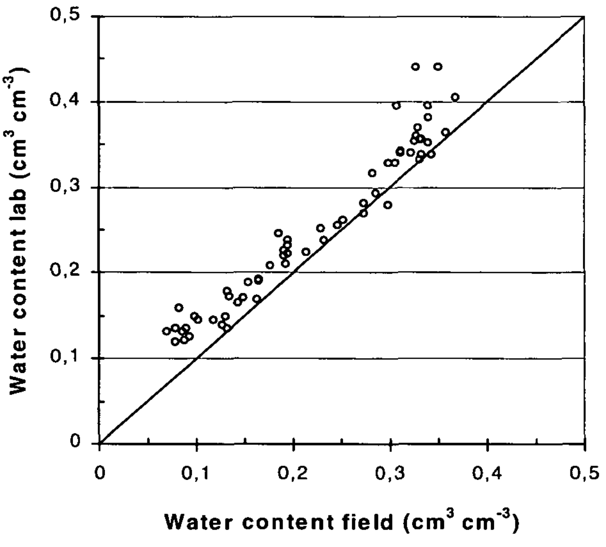


Figure 6.1 Comparison between soil water contents determined on field samples and estimated from water retention curves determined on laboratory data.

6.4.2 Matric potential at field capacity

The average (all soils, all depths) matric potential values after 2 and 5 days of drainage, ψ_{2d} and ψ_{5d} are -7.2 kPa and -9.1 kPa respectively. ψ_{2d} of the whole data set has a standard deviation of 1.9 kPa and extreme values of -11.9 kPa, and -1.6 kPa. These results correspond well with values given by Wolf (1975) and Reichardt (1988).

Table 6.2 presents regression equations of ψ_{2d} and ψ_{5d} against other soil characteristics. Interestingly, ψ_{2d} and ψ_{5d} correlate better with the other soil characteristics for the layers below the considered depth rather than with those at the same depth. Highly significant negative correlation coefficients occur with bulk density and with contents of water-dispersible clay, total clay and coarse sand at 30 cm below the observation depth of ψ (the next observation depth). This suggests that high matric potentials after 2 and 5 days of drainage observed in some soils are associated with water stagnation on dense underlying layers with unstable structure (high content of water-dispersible clay).

Table 6.2 Regression equations expressing the matric potential at field capacity as a function of particle size distribution and bulk density at 30 cm below the control section

Eq. No.	Equation	r^2	Residual variance
A.	$\psi_{2d} = -22.0 + 9.0\,BD_{30} + 5.6\,NClay_{30} + 5.9\,Clay_{30}$	0.45	2.32
	s.e. 2.4 1.5 1.1 1.2		
B.	$\psi_{5d} = -26.9 + 11.1\,BD_{30} + 5.9\,NClay_{30} + 7.0\,Clay_{30}$	0.43	3.42
	s.e. 3.0 1.9 1.4 1.5		
C.	$\psi_{5d} = -30.0 + 10.2\,BD_{30} + 6.4\,NClay_{30} + 12.2\,Clay_{30} + 10.0\,CSnd_{30}$	0.50	3.00
	s.e. 2.9 1.8 1.3 2.1 2.9		

ψ_{2d}: Matric potential (kPa) 2 days after field saturation.
ψ_{5d}: Matric potential (kPa) 5 days after saturation.
BD_{30}: Bulk density (g cm-3) at 30 cm below the control section for matric potential
$NClay_{30}$: Water dispersible clay content 30 cm below the control section for matric potential ($g\,g^{-1}$)
$Clay_{30}$: Total clay content at 30 cm below the control section for matric potential ($g\,g^{-1}$)
$CSnd_{30}$: Coarse sand content at 30 cm below the control section for matric potential ($g\,g^{-1}$)

6.4.3 Soil water content at field capacity

It was found that, on the average, θ_{2d} exceeds θ_{5d} by 0.01 $cm^3\,cm^{-3}$; θ_{2d} exceeds θ_{-10kPa} by 0.013 $cm^3\,cm^{-3}$ and θ_{2d} exceeds θ_{-30kPa} by 0.053 $cm^3\,cm^{-3}$. Residual variances were: $var(\theta_{2d}-\theta_{5d}) = 0.9\ 10^{-3}$; $var(\theta_{2d}-\theta_{-10kPa}) = 5.0\ 10^{-3}$; $var(\theta_{5d}-\theta_{-10kPa}) = 3.4\ 10^{-3}$ and $var(\theta_{2d}-\theta_{-30kPa}) = 11.6\ 10^{-3}$. The small differences between θ_{2d} and θ_{5d} suggest that the error introduced by the assumption that the water flux ceases after a few days of free drainage is small. The average difference between θ_{2d} and θ_{-10kPa} is also small, but marked differences occur in soils with dense layers. The maximum difference between θ_{2d} and θ_{-10kPa} of the data set is 0.11 $cm^3\,cm^{-3}$!

Regression analysis for the water contents θ_{2d}, θ_{5d} and θ_{-10kPa} against other soil attributes (table 6.3) shows positive correlations with (clay+silt%), and negative correlation with iron content. Negative correlation coefficients for Fe_2O_3 reflect that high contents of iron are associated with relatively large and stable microaggregates (pseudosand). At FC, relatively small amounts of water are retained in the pores between these aggregates.

Table 6.3 Regression equations, with standard errors, expressing different approaches to soil water content at field capacity as a function of contents of clay, silt and total Fe_2O_3 (all in $g\,g^{-1}$), bulk density of samples from the control section (BD, $g\,cm^{-3}$) and of samples from 30 cm below the control section (BD_{30}, $g\,cm^{-3}$)

Eq. No.	Equation	r^2	Residual variance
A.	$\theta_{2d} = 0.185 + 0.28$ (Clay+silt) s.e. .0073 0.011	0.85	$11.4\ 10^{-4}$
B.	$\theta_{2d} = 0.169 + 0.39$ (Clay+silt) $- 0.46\ Fe_2O_3$ s.e. 0.0063 0.017 .059	0.90	$7.2\ 10^{-4}$
C.	$\theta_{2d} = 0.068 + 0.42$ (Clay+silt) $- 0.44\ Fe_2O_3 + 0.066\ BD_{30}$ s.e. 0.040 0.020 0.058 0.025	0.91	$6.9\ 10^{-4}$
D.	$\theta_{5d} = 0.175 + 0.28$ (Clay+silt) s.e. 0.0076 0.011	0.85	$11.4\ 10^{-4}$
E.	$\theta_{5d} = 0.159 + 0.39$ (Clay+silt) $- 0.44\ Fe_2O_3$ s.e. 0.0067 0.018 0.061	0.90	$7.7\ 10^{-4}$
F.	$\theta_{5d} = -0.011 + 0.44$ (Clay+silt) $- 0.40\ Fe_2O_3 + 0.11\ BD_{30}$ s.e. 0.039 0.020 0.057 0.025	0.92	$6.5\ 10^{-4}$
G.	$\theta_{-10kPa} = 0.162 + 0.30$ (Clay+silt) s.e. 0.0074 0.011	0.85	$12.0\ 10^{-4}$
H.	$\theta_{-10kPa} = 0.173 + 0.36$ Clay s.e. 0.0077 0.015	0.83	$14.1\ 10^{-4}$
I.	$\theta_{-10kPa} = 0.045 + 0.42$ (Clay+silt) $- 0.37\ Fe_2O_3 + 0.063$ BD s.e. 0.036 0.021 0.063 0.022	0.90	$8.6\ 10^{-4}$
J.	$w_{-30kPa} = 0.029 + 0.36$ (Clay+silt) s.e. 0.0071 0.011	0.90	$10.9\ 10^{-4}$
K.	$w_{-30kPa} = 0.040 + 0.44$ Clay s.e. 0.0069 0.013	0.90	$11.1\ 10^{-4}$

θ_{2d} : soil water retained ($cm^3\,cm^{-3}$) 2 days after field saturation
θ_{5d} : soil water retained ($cm^3\,cm^{-3}$) 5 days after field saturation
θ_{-10kPa} : soil water retained ($cm^3\,cm^{-3}$) at matric potential of -10 kPa
w_{-30kPa} : soil water retained ($g\,g^{-1}$) at matric potential of -30 kPa

6.4.4 Soil water content at the -1.5MPa matric potential

Regression equations relating $\theta_{-1.5MPa}$ and $w_{-1.5MPa}$ to other soil characteristics (table 6.4), compare fairly well with the published equations presented in table 6.1. No significant correlation (at 1% confidence level) was found with organic-C content, as suggested by Pidgeon (1972) and Soil Survey Staff (1992). The regressions were not improved significantly by considering silt content either in combination with clay (i.e clay+silt) or as independent variable.

Table 6.4 Regression equations expressing soil water content at -1.5 MPa matric potential ($\theta_{-1.5MPa}$, $cm^3 cm^{-3}$) in relation to contents of particle size fractions ($g\,g^{-1}$) and bulkdensity (BD, $g\,cm^{-3}$)

Eq. No.	Equation	r^2	Residual variance
A.	$\theta_{-1.5MPa} = 0.020 + 0.27$ (Clay+silt) s.e. 0.0049 0.007	0.92	$5.2\ 10^{-4}$
B.	$\theta_{-1.5MPa} = 0.029 + 0.33$ Clay s.e. 0.0052 0.010	0.90	$6.3\ 10^{-4}$
C.	$w_{-1.5MPa} = \theta_{-1.5MPa}/BD = -0.013 + 0.28$ (Clay+silt) s.e. 0.0033 0.005	0.94	$3.6\ 10^{-4}$
D.	$w_{-1.5MPa} = \theta_{-1.5MPa}/BD = -0.0050 + 0.34$ Clay s.e. 0.0031 0.006	0.95	$3.5\ 10^{-4}$

6.4.5 Estimates of AWC

The average value of $\theta_{2d-1.5MPa}$ is 0.169 $cm^3 cm^{-3}$ The minimum $\theta_{2d-1.5MPa}$ value is 0.11 $cm^3 cm^{-3}$ and the maximum 0.24 $cm^3 cm^{-3}$. Even considering a possible overestimation of up to 0.04 $cm^3 cm^{-3}$ due to discrepancy with field data, these results support the evidence presented by Van den Berg et al. (1997) that AWC of strongly weathered soils may be considerably greater than the "indicative" or "reference" values suggested by e.g. Sanchez (1981), Wambeke (1974), Elsevier (1981, p.75) and Batjes (1995). Low AWC-values that are commonly reported are explained by the use of water potentials of -30 or -33 kPa to assess FC and perhaps also by the fact that water retention is still often determined on disturbed (crushed and sieved) soil samples. Aina & Periaswamy (1985) found that the water contents of crushed soil materials exposed to a water potential of -33 kPa were on the average 0.034 $g\,g^{-1}$ less than those of soil cores.

Regression equations for the different approaches to AWC (table 6.5) show a rather poor fit, but residual variances are less than the ones for FC, and only slightly larger than the pooled variance of the three replicates. It seems unlikely that equations can be developed (for the studied soils) that are much better than the ones presented. The different AWC approaches were not significantly correlated with organic-C content, or with contents of clay or clay+silt when taken as a single independent variable. Figure 6.2 shows that the relations θ_{2d} and $\theta_{-1.5MPa}$ as functions of clay+silt content are parallel, with

Table 6.5 Regression equations expressing different approaches to available water capacity in relation to particle size fractions ($g\,g^{-1}$), difference between bulk density of samples from the control section and from 30 cm below the control section ($BD_{dif} = BD\text{-}BD_{30}$, $g\,cm^{-3}$) and total Fe_2O_3 content ($g\,g^{-1}$)

Eq. No.	Equation	r^2	Residual variance
A.	$\theta_{2d\text{-}1.5MPa} = 0.165 + 0.077\,(Clay+Silt) - 0.141\,BD_{dif} - 0.317\,Fe_2O_3$ s.e. 0.0060 0.015 0.028 0.05	0.35	$5.7\ 10^{-4}$
B.	$\theta_{5d\text{-}1.5MPa} = 0.154 + 0.075\,(Clay+Silt) - 0.119\,BD_{dif} - 0.30\,Fe_2O_3$ s.e. 0.0060 0.018 0.028 0.051	0.32	$5.4\ 10^{-4}$
C.	$\theta_{-10kPa\text{-}1.5MPa} = 0.133 + 0.082\,(Clay+Silt) - 0.25\,Fe_2O_3$ s.e. 0.0062 0.017 0.057	0.17	$7.2\ 10^{-4}$

considerable scatter in the differences θ_{2d} -$\theta_{-1.5MPa}$. Important factors that appear to be correlated with $\theta_{2d\text{-}1.5MPa}$ are (1) vertical differentiation in bulk density, and (2) the Fe_2O_3 content. This does not mean that dense layers or unstable structures enhance the availability of water to crops, because the same phenomena hinder root penetration and water movement.

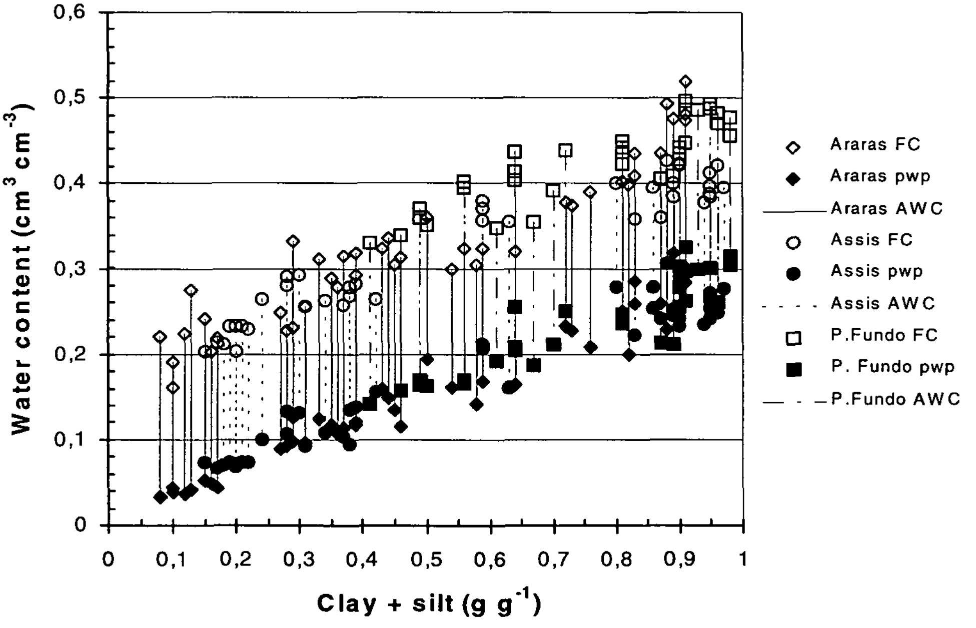


Figure 6.2 Relation between soil water content after 2 days of field saturation (open symbols) and at soil water potential of -1.5 Mpa (closed symbols), with clay+silt contents. Stack lengths represent AWC.

Comparison between the results of this study and the formerly published results resumed in table 6.1, is difficult because different analytical methods were used and in some cases different dependent variables were included in the regression equations. It seems clear however that relations obtained in different regions or from a worldwide data-set, cannot be used to differentiate strongly weathered soils at a local level with respect to AWC.

Farmers and extension officers in Brazil contend that strongly weathered clay soils are less prone to drought than sandier ones. This is not supported by the AWC approximations presented here (figure 6.2), nor by the study on the world-wide data set of Ferralsols and related soils by Van den Berg et al (1997), and several of the other authors quoted in table 6.1. Future studies should focus on this paradox. Such studies should make more detailed field observations and pay attention to hysteresis, differences between field and laboratory soil water data, root distribution and chemical root barriers (e.g. Al toxicity).

6.5 Conclusions

1. Water loss by percolation through the soils in the study areas is small after 2 days of drainage; it can be ignored in studies of water availability to plants in the selected regions.

2. Matric potential at field capacity (determined in the field after 2 days of drainage) is normally between –10 kPa and -6 kPa for the studied (strongly weathered) soils.

3. Field capacity studies should consider entire soil profiles, not just the layers or horizons of interest.

4. Indicative values of 0.10 $cm^3\,cm^{-3}$, as often mentioned in textbooks, seem to generally underestimate the AWC of strongly weathered soils.

5. Farmers' perception of differences in drought stress on strongly weathered soils with clayey and sandy textures in South and South East Brazil are not explained by application of the AWC concept.

7. WATER RETENTION CHARACTERISTICS

7.1 Introduction

7.1.1 Problem and objectives

Indications of field capacity (FC), permanent wilting point (PWP) and available water capacity (AWC) as discussed in chapter 6, are often considered insufficient for (modelling) studies on water sufficiency in land use systems analysis. Important additional data required are, among others, soil water retention characteristics, i.e. descriptions of the relations between soil water content (θ, $cm^3 cm^{-3}$) and the matric component of soil water potential (ψ, kPa). Determination of these characteristics is costly and time consuming (analysis of a sample takes $\pm$ 10 weeks). Therefore, it is considered important to investigate relations between this difficult-to-obtain information and routinely-determined soil properties (RDP's). Once validated, the relations could be used as "transfer functions" to predict soil water characteristics from RDP's; and incorporated in simulation models.

Two types of transfer functions for soil water retention characteristics can be distinguished (Rawls et al., 1991):

1) Point estimation: functions that relate θ at several fixed values of ψ to RDP's. Soil water content at intermediate ψ is predicted by curve fitting or interpolation;

2) Parameterisation: functions that relate parameters of a descriptive equation of θ against ψ to RDP's. Soil water content at any ψ is predicted by substituting ψ and the predicted parameter values in the descriptive equation.

Tietje & Tapkenhinrichs (1993) consider a third type: physical-conceptual models. However, such models either assume very simple pore geometry, or require so much detailed information that they cannot be considered transfer functions, or contain empirical components, by which they become in fact models of type 1 or 2.

A disadvantage of type 1 is that disturbing artefacts (e.g. tracks with increasing θ on decreasing ψ) may appear when $\theta(\psi)$ is plotted as a function, especially when extrapolations are made outside the range of the original RDP's (Tietje & Tapkenhinrichs, 1993). Artefacts are avoided more easily in type 2, by a proper choice of the descriptive equation. Furthermore, transfer functions of type 2 yield continuous $\theta(\psi)$ relations which, once available, are easier to apply and to be incorporated in simulation models.

A widely used descriptive $\theta(\psi)$ equation is the one proposed by Van Genuchten (1980). Transfer functions for Belgian soils, based on this equation were published by Vereecken et al. (1989). The Netherlands' foundation for soil survey (STIBOKA) provides parameter estimates for this equation for each soil texture class (Wösten et al., 1986). The Soil Data Task of IGBP-DIS (1998) agreed to develop transfer functions of type 2 to predict the parameters of the Van Genuchten equation and to use the resulting curves to predict available water capacity (AWC), by subtracting the predicted value of water content at -1.5MPa ($\theta_{-1.5MPa}$) from the prediction of e.g. θ_{-10kPa} or θ_{-33kPa}.

Van den Berg et al. (1997) and Tomassella & Hodnett (1998) argue that transfer functions derived from soils in temperate regions appear to be inadequate for strongly weathered soils. These soils have somewhat particular water retention curves. Their typically sigmoid shape and the relatively large content of residual water, suggest that they behave like sands when wet, turning to behave like clay on drying. This is explained by the strong micro-structure of these soils, with silt-sized and sand-sized micro-aggregates, composed of clay particles bound by sesquioxides (Sharma & Uehara, 1968). Most soil water retained between micro-aggregates is released at soil water potential >-80 kPa, whereas a considerable amount of water remains in the small pores within aggregates of clayey soils, even when soil water potential decreases below -1.5MPa.

Tomasella & Hodnett (1998) developed transfer functions for (mostly strongly weathered) soils of Brazilian Amazonia, using an equation proposed by Brooks & Corey (1964), but suggest that the equation of Van Genuchten (1980) may be more appropriate for these soils. Van den Berg et al (1997), tested transfer functions of type 1 and type 2 for a world wide data set on Ferralsols and related strongly weathered soils, sampled and analysed by uniform methods at the International Soil Reference and Information Centre (ISRIC), Wageningen. They found that the equation proposed by Van Genuchten (1980) was suitable for description of their water retention curves, although it tended to slightly overestimate the amount of water retained between -10 kPa and -1.5 MPa ($\theta_{-10kPa-1.5MPa}$). Strong correlations were found for soil water content at -10 kPa (θ_{-10kPa}) and at -1.5 MPa ($\theta_{-1.5MPa}$) against RDP's, but predictions of $\theta_{-10kPa-1.5MPa}$ were disappointing. Direct predictions (i.e. transfer functions of type 1) were consistently better than predictions of parameters of the equation proposed by Van Genuchten (1980), followed by the application of that equation to estimate key soil water contents or $\theta_{-10kPa-1.5MPa}$.

An underlying hypothesis of the present study is that more encouraging results might be obtained if a somewhat narrower data set is used, in this case only comprising strongly weathered soils from the study regions in South and South-East Brazil.

The objectives of this study are: (i) evaluate the applicability of the equation of Van Genuchten (1980) to describe water retention characteristics of strongly weathered soils in South and South-East Brazil; and (ii) to explore possibilities to predict water retention curves of soils from the study regions from RDP's.

The accuracy of predictions of θ_{2d} to represent field capacity (FC); of $\theta_{-1.5MPa}$ to represent permanent wilting point (PWP) and of $\theta_{2d-1.5MPa}$ as a surrogate for available water capacity (AWC), all defined in chapter 6, were used as a yardstick for the quality of the transfer functions.

7.1.2 The Van Genuchten Equation

The semi-empirical mathematical expression for description of the water retention curve proposed by Van Genuchten (1980) can be written as:

$$S_e = [1 + (\alpha|\psi|)^n]^{-m} \quad (7.1)$$

where,

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \quad (7.2)$$

and

- S_e is "effective saturation" (dimensionless);
- $|\psi|$ is the absolute value of the matric potential (kPa);
- θ is momentary (actual) volumetric soil water content ($cm^3 cm^{-3}$);
- θ_s is saturated water content ($cm^3 cm^{-3}$);
- θ_r is "residual water content" ($cm^3 cm^{-3}$), i.e. water content for which the gradient $d\theta/d\psi$ becomes nil, at very low potentials;
- α is a parameter, the inverse of which, $1/\alpha$, is an indication of the absolute value of the matric potential at the air entry point (kPa^{-1});
- n and m are dimensionless parameters related to the homogeneity of pore size distribution.

Van Genuchten (1980) suggested that m could be set to $1-1/n$. This usually causes a negligible loss of goodness of fit, and permits another equation to be solved, relating hydraulic conductivity to θ. Small values of n (e.g. <2.) indicate well expressed sigmoidal curves and a homogeneous pore size distribution (Van Genuchten & Nielsen, 1985; Hopmans & Overmars, 1986). However, the parameters α, θ_r, n and m lack a clear physical definition. They must be determined empirically, by curve fitting. This is done by making a number (say 10) of observations of (θ, ψ) data pairs, followed by the determination of the parameter values that provide the best fit through these data. Van Genuchten et al. (1991), developed a computer programme for this purpose, called RETC, which applies an iterative least squares method.

7.2 Materials and methods

7.2.1 Soils

The data used in this study refer to the same soils and samples as used in the previous chapter: 126 layers of 30 strongly weathered soils of the regions surrounding Araras (São Paulo State), Assis (São Paulo State) and Passo Fundo (Rio Grande do Sul), Brazil.

The data were divided in two sets: Set 1: Araras and Assis (93 layers of 23 profiles) to develop transfer functions; and set 2: Passo Fundo (33 layers of 7 soils), to make an independent set to test the transfer functions.

7.2.2 Basic data

The determinations of θ_{2d} ($cm^3 cm^{-3}$), $\theta_{-1.5MPa}$, $\theta_{2d-1.5MPa}$, bulk density (BD, $g\,cm^{-3}$) and water retention curves are described in chapter 6.

The following RDP's were correlated with the retention data: soil texture (contents of water dispersable clay, total clay, silt and coarse sand, $g\,g^{-1}$), contents of organic carbon, total Fe_2O_3 and total Al_2O_3 ($g\,g^{-1}$) and bulk density (BD, BD_{30}, $g\,cm^{-3}$). Methods of determination are given in chapter 6.

7.2.3 Development of transfer functions and their assessment

The Van Genuchten equation (equations 7.1+7.2) was fitted through the water retention data for each depth of each soil profile. The parameters α, θ_r, θ_s, m and n were estimated using the aforementioned computer programme RETC (Van Genuchten et al., 1991). The appropriateness of the equation was tested by comparing the original θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ data with results obtained by substituting ψ_{2d}, $\psi_{-1.5MPa}$ and the predicted parameter values in the descriptive equation; and, in case of $\theta_{2d-1.5MPa}$, subtracting the resulting values.

Stepwise multiple regression was applied to data set 1, to correlate (1) θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ against RDP's; and (2) the parameters of equations 7.1 and 7.2 against RDP's. In most cases linear models were fitted, but in a few instances graphical representations suggested curvilinear relations.

This resulted in two types of transfer functions:
Type 1: Transfer functions to predict θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ directly;
Type 2: Transfer functions to predict parameters of the Van Genuchten equation.

Predicted values of θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ for transfer functions of type 1 were obtained by substituting measured RDP values of data set 2 (the independent data set) in the respective transfer functions. Predicted values for transfer functions of type 2 were obtained by first substituting measured RDP values of data set 2 in the transfer functions to predict Van Genuchten parameters, followed by substituting these predicted parameters and ψ_{2d} or $\psi_{-1.5MPa}$ in the Van Genuchten equation, and subtraction in case of $\theta_{2d-1.5MPa}$.

The accuracy of θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ predictions was quantified in terms of the bias (average prediction error, APE), the mean variance of the prediction errors (MVPE) and the mean squared error of prediction (MSEP), defined as:

$$APE = (1/n)\,\Sigma_{i=1,n}\,(y_i - \hat{y}_i) \quad (7.3)$$

$$MVPE = \mathrm{var}\,(\hat{y}_i - y_i) \quad (7.4)$$

$$MSEP = (1/n)\,\Sigma_{i=1,n}\,(\hat{y}_i - y_i)^2 \quad (7.5)$$

where,

y_i is the measured value of the i^{th} observation of the variable of interest *Y;*
$\hat{y}_i$, the predicted value of the i^{th} observation of variable *Y;*
n, the total number of observations (not to be confused with parameter *n* of equation 7.1).

7.3 Results

7.3.1 Application of the Van Genuchten equation

Preliminary data screening showed that several parameters of the Van Genuchten equation are strongly correlated. Setting *m* to 1-1/*n* did not notably decrease the goodness of fit.

Some of the water retention data of the Araras and Assis regions and all of the Passo Fundo region, appear to be present a discontinuity between matric potentials of -200 and -800 kPa. This is probably an analytical error, caused by a change of measurement method (from core samples to disturbed samples). Fitted residual soil water content (θ_r) becomes nil for these samples, whereas relatively large θ_r values were determined for similar samples (e.g. of an adjacent layer in the same profile with similar morphology) that showed a gradual water release between -0.2 and -0.8 MPa. The histogram of θ_r, presented in figure 7.1, shows a clear bimodal distribution, with peaks at 0.0 and between 0.05 and 0.1 $cm^3 cm^{-3}$. Regression equations using θ_r as dependent variable and routinely-measured soil characteristics as independent variables do not "explain" this.

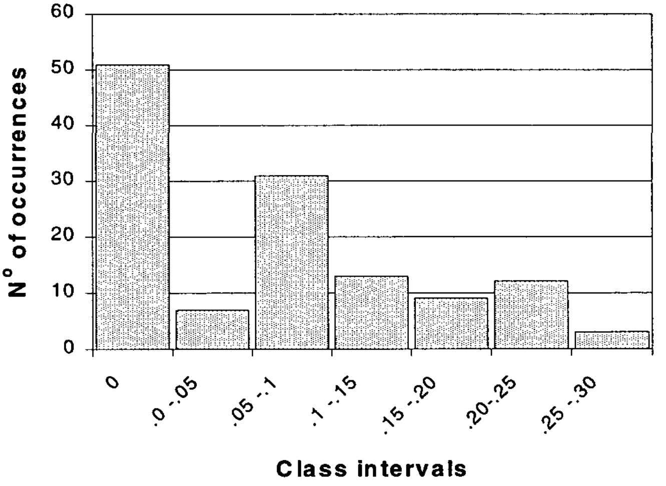


Figure 7.1 Histogram of residual water contents (θ_r, $cm^3 cm^{-3}$) calculated by application of the RETC programme to the Van Genuchten model (equations 7.1 and 7.2)

If θ_r is set to 0. for all curves (as was done by Wösten & van Genuchten, 1988, for soils with high activity clays), considerable discrepancy between fitted and observed data appears. Setting the value of θ_r to a positive value obtained by regression with clay+silt and organic-C (using the samples with fitted $\theta_r > 0$; see table 7.3, equation A), gave satisfactory results, even for samples with fitted $\theta_r = 0$. Figure 7.2 compares some curves with θ_r fitted independently, and θ_r set to a value calculated with the regression equation.

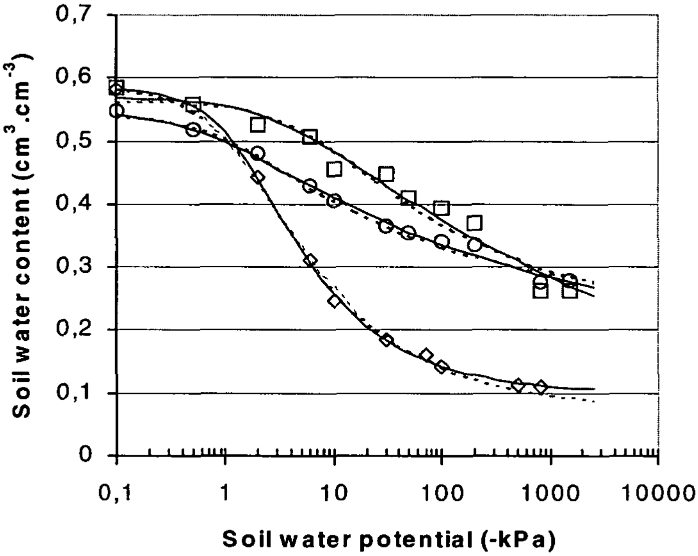


Figure 7.2 Water retention data and fitted "Van Genuchten" equations of selected soil samples. Solid lines: θ_r fitted independently; dashed lines: θ_r fixed by equation A of table 7.3. Observed values: diamonds: Araras, sandy clay loam; squares: Assis, clay soil; circles: P.Fundo, clay soil

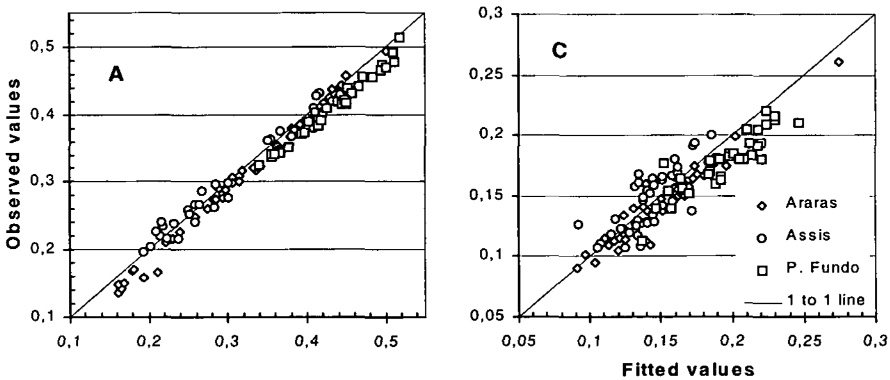
Statistics of the obtained Van Genuchten parameters are summarized in table 7.1. Parameter α showed a strongly skewed distribution and was transformed to $\ln(\alpha)$. Figure 7.3 compares measured values of θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ with values obtained by substituting fitted parameter values into equations 7.1 and 7.2.

7.3.2 Transfer functions for the prediction of soil-water relations

Table 7.2 presents regression equations for θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$, correlated with RDP's, for dataset 1 (Araras and Assis). Table 7.3, presents regression equations for the parameters of the Van Genuchten equation, correlated with RDP's, also for dataset 1. These equations were used as transfer functions. For α, the values were estimated simply from the average of $\ln(\alpha)$ from data set 1, because none of the RDP's showed significant correlation (at 5 % level) with α.

Table 7.1 Summary statistics of parameters of the Van Genuchten equation, fitted by RETC (θ_r estimated by equation A of table 7.3)

	θ_r	θ_s	$\ln(\alpha)$	n
Araras				
Minimum	0.000	0.383	-1.89	1.138
Maximum	0.251	0.721	0.97	1.660
Average	0.106	0.517	-0.43	1.347
Standard deviation	0.065	0.081	0.58	0.145
Assis				
Minimum	0.063	0.342	-1.71	1.117
Maximum	0.235	0.650	1.23	1.507
Average	0.139	0.493	-0.53	1.314
Standard deviation	0.058	0.090	0.33	0.098
Passo Fundo				
Minimum	0.013	0.350	-4.96	1.073
Maximum	0.250	0.563	0.15	1.222
Average	0.167	0.468	-3.11	1.156
Standard deviation	0.064	0.055	1.88	0.034



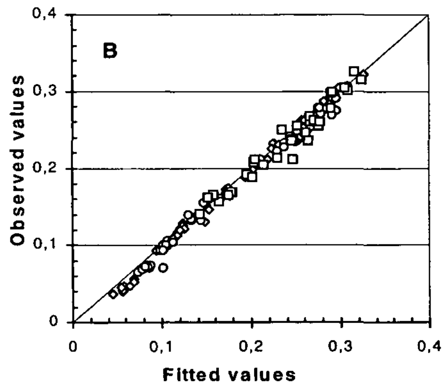


Figure 7.3 Comparison of observed values of A: θ_{2d}; B: $\theta_{-1.5MPa}$ and C: $\theta_{2d-1.5MPa}$ (all in $cm^3\ cm^{-3}$) with those fitted according to the Van Genuchten equation.

Table 7.2 Regression equations for θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ for data set 1 (Araras and Assis)

N°	Equations and standard errors (s.e.) of the regression parameters	r^2	Residual variance
A.	θ_{2d} = 0.169 + 0.26 (Clay+Silt) - 0.81 Fe_2O_3 + 0.46 Al_2O_3 s.e. 0.171 0.041 0.089 0.18	0.90	6.9 10^{-4}
B.	$\theta_{-1.5MPa}$ = BD [-0.0100 + 0.27 (Clay+Silt)] s.e. 0.0025 0.004	0.97	2.0 10^{-4}
C.	$\theta_{2d-1.5MPa}$ = 0.263 – 0.125 BD + 0.065 BD_{30} - 0.18 Fe_2O_3 s.e. 0.030 0.030 0.034 0.05	0.25	5.3 10^{-4}

Clay, Silt, Fe_2O_3, Al_2O_3: $g\,g^{-1}$; BD: bulk density ($g\,cm^{-3}$); BD_{30}: BD at 30 cm below layer to which dependent variable refers.

Table 7.3 Regression equations for parameters of the Van Genuchten equation (eq. 7.1 and 7.2) for data set 1 (Araras and Assis).

N°	Equations and standard errors (s.e.) of regression parameters	r^2	Residual variance
A.	θ_r = 0.064 + 0.19 $(Clay+Silt)^2$ - 268 C^2 s.e. 0.0051 0.011 59	0.91	8.0 10^{-4}
B.	θ_s = 0.88 - BD (0.31 Sand + 0.27 Silt) s.e. 0.031 0.019 0.029	0.86	9.1 10^{-4}
C.	n = 1.74 - 0.36 BD + 0.007 CSand - 0.106 C s.e. 0.035 .030 0.0004 0.011	0.88	19 10^{-4}
D.	$\ln(\alpha)$ = -0.48 s.e. 0.019	-	0.35

Clay, Silt, Coarse Sand, organic C: $g\,g^{-1}$; BD: bulk density ($g\,cm^{-3}$)

Table 7.4 Analysis of variance of estimates for soil-water characteristics

		Data set 1												Data set 2			
		Complete data set				Araras				Assis				Passo Fundo			
Vari-able	Type	tot var (a)	MEP (b)	MV PE (a)	MS EP (a)	tot var (a)	MEP (b)	MV PE (a)	MS EP (a)	tot var (a)	MEP (b)	MV PE (a)	MS EP (a)	tot var (a)	MEP (b)	MV PE (a)	MS EP (a)
θ_{2d}	1	74	-0.6	6.8	7.2	78	-0.4	8.2	8.4	58	0.3	5.2	5.3	24	-2.0	4.8	8.8
cm^3cm^{-3}	2		0.7	10.5	10.9		1.0	7.0	7.9		1.3	9.4	11.2		-0.6	14.8	15.2
$\theta_{-1.5MPa}$	1	63	0.0	3.4	3.4	69	0.2	1.9	1.9	65	-0.2	1.9	2.0	28	-0.1	7.8	7.8
cm^3cm^{-3}	2		-0.1	10.4	10.5		0.8	4.3	4.9		-0.7	8.3	9.5		-0.7	21.2	21.7
$\theta_{2d-1.5MPa}$	1	9.1	-0.7	6.1	6.6	8.3	-0.7	5.9	6.4	4.5	0.6	3.5	3.9	6.7	-2.3	4.9	10.2
cm^3cm^{-3}	2		0.6	6.6	7.0		0.2	7.9	7.9		2.0	5.2	9.2		-0.2	6.1	6.1
Avr = 0.169			-0.8	9.1	9.7		-1.2	8.3	9.7		1.3	4.5	6.2		-2.8	6.7	14.5

(a) Multiply values by 10^{-4}; (b) multiply values by 10^{-2}

Figure 7.4 shows results of the different types of transfer functions as 1:1 scatter diagrams. A summary of statistics is given in table 7.4. Note that, to simplify comparison, results of data sets 1 and 2 are presented in the same way, although results of set 1 are not real predictions, i.e. they were not obtained independently. In the case of $\theta_{2d\text{-}1.5MPa}$, results of another "transfer function" are reported at the bottom of table 7.4: a simple estimate by the average value of data set 1, which was 0.169 $cm^3 cm^{-3}$.

7.4 Discussion

7.4.1 Application of the Van Genuchten equation to describe water retention curves

The Van Genuchten equation could well accomodate the observed data but is perhaps too flexible, as indicated by the strong correlation between some of the parameters (notably n and m) and by the strong effect on θ_r of small discontinuities in the $\theta(\psi)$ observations. The suggestion of Van Genuchten et al. (1991) to link n and m and apply several iterations of data screening, fixing parameter values and fitting the equation with the optimisation programme is appropriate. Van den Berg et al. (1997) noted a tendency to slightly overestimate large values of $\theta_{2d\text{-}1.5MPa}$ after fitting the Van Genuchten equation. This tendency seems to be confirmed in figure 7.3 C, but is rather inexpressive in comparison to the overall scatter.

Discontinuity in several water retention data, between -200 and -800 kPa, is probably an artefact, related with the change of laboratory method, from undisturbed core samples to disturbed samples. The effect may have been aggravated by rupture of pores within samples during sampling or transport. Discontinuity in all $\theta(\psi)$ observations of the Passo Fundo region may be related with the somewhat stronger macro structure and higher bulk density observed in the soils of that region. This kind of discontinuities between results from undisturbed and disturbed samples are quite common (ISRIC, personal communication) but rarely published, because the curves can easily be smoothed by manual fitting. This study shows that they can cause a considerable change of parameter values obtained by automatic curve fitting.

7.4.2 Application of transfer functions

One can infer from figure 7.4 and table 7.4 that both types of transfer functions provide reasonably adequate predictions of θ_{2d} and $\theta_{-1.5MPa}$, but predictions of $\theta_{2d\text{-}1.5MPa}$ are rather poor. Type 1 (obtained from direct regression) generally produces superior predictions (smaller MVPE and MSEP) than type 2 (using the Van Genuchten equation). This was also the case in the study of Van den Berg et al. (1997). An exception in the present study is the better performance of the transfer functions of type 2 to predict $\theta_{2d\text{-}1.5MPa}$ for data set 2. This appears to be a "coincidence", because the errors in both components of $\theta_{2d\text{-}1.5MPa}$: θ_{2d} and $\theta_{-1.5MPa}$, are larger for type 2 than for type 1.

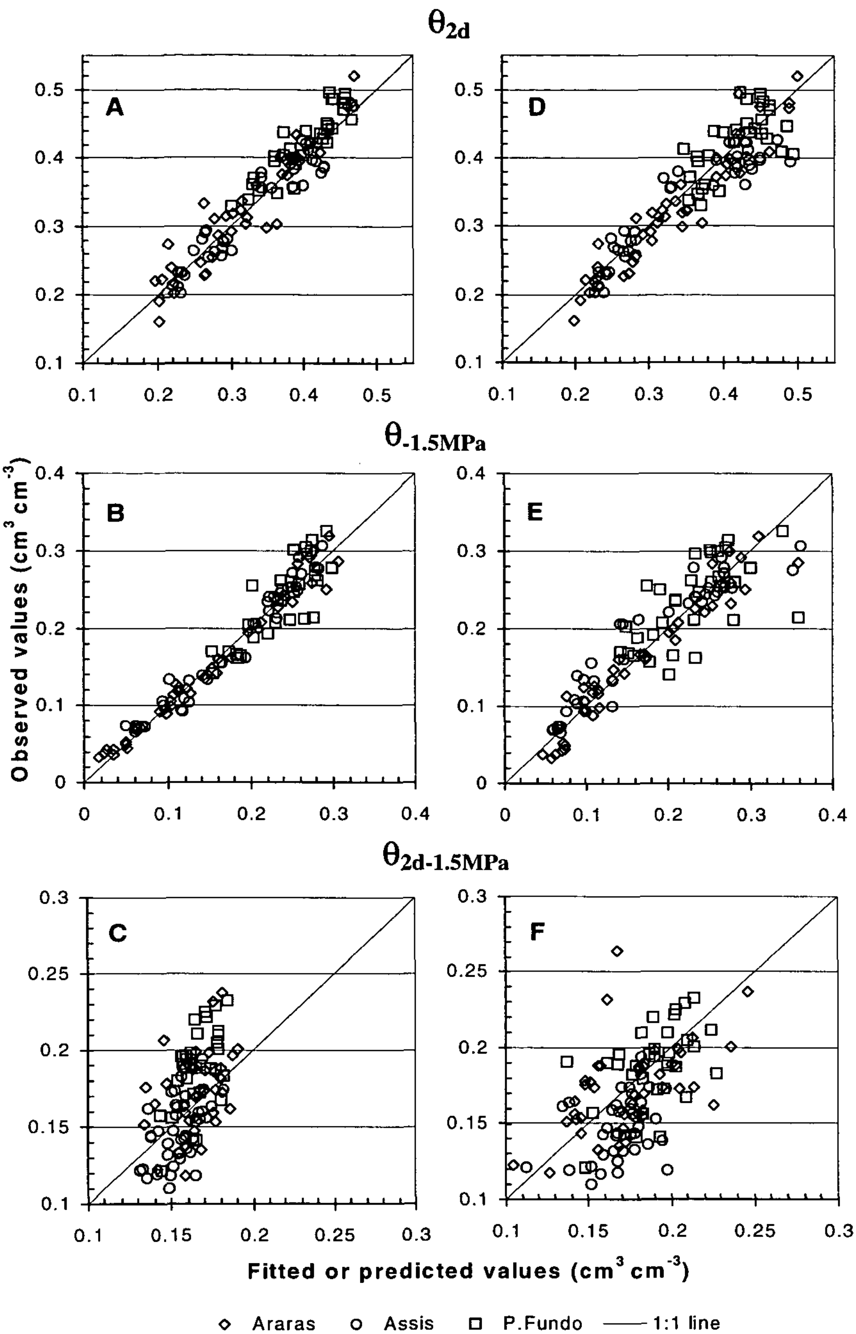


Figure 7.4 Comparison between observed and fitted or predicted values of θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$. Fitted: set 1, Araras and Assis; predicted: set 2, Passo Fundo. A, B and C: calculations with transfer functions of type 1 (direct); D, E and F: calculations with transfer functions of type 2 (using Van Genuchten equation).

Note that for $\theta_{2d\text{-}1.5MPa}$, in general MVPE is only slightly less than total variance; in some cases even more. The transfer functions did not manage to explain differences in $\theta_{2d\text{-}1.5MPa}$ between soils of the same region. Using the average $\theta_{2d\text{-}1.5MPa}$ value of dataset 1 (0.169 $cm^3 cm^{-3}$, table 7.3) gives almost the same error as the $\theta_{2d\text{-}1.5MPa}$ values obtained by application of the transfer functions.

Five factors contribute to the apparently poor performance of the transfer functions for $\theta_{2d\text{-}1.5MPa}$:

1) propagation of errors from each parameter in the descriptive model, aggravated by subtracting $\theta_{-1.5MPa}$ from θ_{2d};

2) errors in observed water retention data;

3) other variables than RDP's determine $\theta_{2d\text{-}1.5MPa}$;

4) relations between RDP's and water retention data are more complex than the linear regression models used; and

5) $\theta_{2d\text{-}1.5MPa}$ is less variable than θ_{2d} and $\theta_{-1.5MPa}$, i.e. there is less variance to be resolved.

The first aspect is only relevant for transfer functions that are based on parameterisation (type 2). It is therefore expected that, unless the descriptive model used is based on physical laws (which is not the case) transfer functions of type 2 are generally less suited to predict specific points on the water retention curves than transfer functions of type 1. This seems to have been overlooked by IGBP-DIS (1998) and Kern (1995). The latter evaluated different transfer functions of type 2 for soils of the United States of America. He compared thousands of $\theta_{-1.5MPa}$, θ_{-33kPa} and θ_{-10kPa} predictions with observed data and discussed the results in relation to their relevance with respect to plant-available-water-holding-capacity, but he did not present results on the adequacy of $\theta_{-33kPa\text{-}1.5MPa}$ or $\theta_{-10kPa\text{-}1.5MPa}$ predictions, which, as inferred from the standard deviations of the prediction errors of θ_{-10kPa}, θ_{-33kPa} and $\theta_{-1.5MPa}$, seem to be quite poor.

Several dynamic models to calculate irrigation needs or to simulate crop growth, [e.g. PS123 (Driessen, 1997) and SWAP (Van Dam et. al., 1997)] require a complete water retention curve. In well drained strongly weathered soils, having good estimates of AWC might be more important than having good "average water retention curves". The results of this study support the suggestion of Van den Berg et al. (1997) that, in such cases, one might apply transfer functions of type 1 to predict e.g. $\theta_{2d\text{-}1.5MPa}$, $\theta_{-1.5MPa}$ (to represent AWC and PWP), θ_r and θ_s, or θ_s-θ_{2d}. Having these values, it is possible to resolve the Van Genuchten equation for α and n and generate complete curves. When more accurate AWC data are needed, it seems necessary to determine at least θ_{2d} in the field. Results obtained with this procedure should be carefully evaluated when models are used that combine transfer functions for water retention with descriptive equations for hydraulic conductivity.

7.5 Conclusions

1. The Van Genuchten equation can be used adequately to describe water retention curves of strongly weathered soils of South and South-East Brazil.

2. θ_{2d}, $\theta_{-1.5MPa}$ and parameter values for the Van Genuchten equation can be predicted from bulk density, particle size distribution, Fe_2O_3 and Al_2O_3 contents, but predictions of θ_{2d}, $\theta_{-1.5MPa}$ and $\theta_{2d-1.5MPa}$ are better when using transfer functions that relate these variables directly to RDP's than using transfer functions that first predict parameters of the Van Genuchten equation. Users of simulation models and evaluators of different soil water retention models should realise this.

[1] The soil water potential ψ is composed of osmotic potential, pressure potential and matric potential. In unsaturated soils, the pressure potential is nil and the osmotic potential is negligible in strongly weathered soils.

PART IV

SUMMARY CROP MODELS. APPROACHES TO SELECTED PROCESSES AND APPLICATION

8. WATER UPTAKE IN SUMMARY CROP GROWTH MODELS. I. APPROACHES AND THEIR PEDIGREES

8.1 Introduction

It is obvious that water limited crop yields, under given meteorological conditions, depend not only on the amount of water that can be temporarily stored over a given depth of soil, as discussed in Chapters 6 and 7, but also on rooting habits, leaf area dynamics, adaptive mechanisms etc... It is not sensible to address these dynamic features with static approaches such as the regression analysis of the previous chapters. Dynamic crop growth simulation models have been designed to cope with them. As mentioned in Chapter 1, simplified, so-called summary crop growth models seem most appropriate for use in land use systems analysis (Rabbinge & De Wit, 1989; Dumanski & Onofrei, 1989; Driessen, 1997). Their aim would - in this context - be to provide reliable estimates of water limited crop yield potentials, over a wide range of environmental conditions, on the basis of available or easily measured data.

Water uptake through roots and loss by transpiration through leaves is such an important process in relation to crop growth that its accurate description deserves special attention. Transpiration is the most important loss component of the energy balance of a crop. In the plant, water is indispensable for transport of organic and inorganic substances, the maintenance of turgor and for chemical reactions in the protoplasm (e.g. Pugnaire et al, 1999). Many crop yield models assume a linear relation between transpiration and photosynthesis considering that carbon dioxide diffusion from the atmosphere into the plant is only possible when leaf stomata are open and water vapour can diffuse from the plant into the atmosphere (e.g. Van Keulen & van Laar, 1986; Penning de Vries et al., 1989). Other effects of water shortage accounted for in some summary crop growth models include increased death rate of leaves, shift in assimilate partitioning favouring root growth (Brouwer, 1963; Sepaskhah & Boersma, 1979), storage of assimilates as carbohydrate reserve (e.g. in sugarcane, Thompson & Boyce, 1968) and increased rate of seed ripening (Costa & Marchezan, 1982).

In the past decades, many descriptions, simulations and calculations of crop water uptake in response to conditions of plant, soil and atmosphere have been developed. The approaches vary widely from theoretical ones based on physical laws of flow in porous media to approaches that are essentially intuitive extrapolations of observed cause-effect relationships, at systems level.

Refined models to describe water flow from the soil through the plant into the atmosphere are not suited for land use systems analysis because they require numerical input data on e.g. diurnal variation of atmospheric conditions, root density distribution and impedance of plant organs and soil to water movement. Such data are non-existent at farm or regional level.

A first look at simple approaches reveals a rather confusing - sometimes conflicting - diversity of concepts and terminology. The objectives of this chapter are (1) to discuss simple approaches to water uptake within their historical/evolutionary perspective, in an attempt to identify reasons for discrepancies (2) to indicate for which conditions different approaches seem most appropriate and (3) to identify topics that need priority for further investigation. The chapter does not address the calculation of potential transpiration and considers only the effects of water shortage on water uptake and crop growth, and not the effects of other factors such as soil salinity and aeration.

The chapter is structured as follows. Section 8.2 describes briefly the backgrounds of established concepts and of published simple approaches to crop water uptake that have been - or could be - applied in summary crop growth models. Section 8.3 discusses the reasons for discrepancies and the strengths and weaknesses of the different approaches, followed by an indication of research priorities. The conclusions are given in section 8.4. The concepts and approaches reviewed are addressed in the following order:

- Upper and lower limits of available soil water and readily available soil water
- The electrical analogue
- Simplifications of the electrical analogue
- Approaches that focus on soil water potential
- Approaches that focus on (relative) soil water content
- Approaches with special attention to evaporative demand of the atmosphere
- Approaches with special attention to non-uniform water uptake

8.2 Established concepts and approaches

8.2.1 Upper and lower limits of available soil water and readily available soil water

Many simple water uptake models are based on the concept that soils behave like a water reservoir with fixed dimensions defined by pore geometry and depth of rooting. Only part of the water that can be stored in this conceptual reservoir is available to plants. A selection of terms related to this concept is given in table 8.1.

Field capacity (FC) is often taken as the upper limit of plant available soil water. This concept stems from observations that water discharge from an initially saturated, freely draining soil tends to cease within a few days, even when a considerable amount of water remains in the soil (Alway & McDole, 1917; Veihmeier & Hendrickson, 1931). Whether and when (pseudo) equilibrium is actually reached and at which soil water content, depends on the initial conditions, on the relations between soil water content (θ), hydraulic conductivity (K) and soil water potential (ψ) throughout the soil, and on the depth of groundwater (Ahuja & Nielsen, 1990). However, for practical purposes, FC is often used as if it were a soil constant. The concept has been further simplified and water content of ground and sieved samples at -33 kPa matric potential (θ_{-33kPa}) is often used to represent soil water content at FC (θ_{fc}). Larger potentials (e.g. -10 kPa) have been suggested for coarse textured soils and strongly weathered soils (Van Wambeke, 1974; Lal, 1979b). Results by e.g. Miller (1973) and Van den Berg (1996) illustrate the

Table 8.1 Terminology of soil water availability

Term	Definition	source
Drained upper limit (DUL)	The highest field-measured water content of a soil after it has been thoroughly wetted and allowed to drain until drainage becomes practically negligible.	Ratliff et al., (1983).
Lower limit (LOL)	The lowest field-measured water content of a soil after plants stop extracting water and are at or near premature death or become dormant as a result of water stress.	Ratliff et al., (1983).
Potential extractable soil water (PLEXW)	The difference in water content between DUL and LOL.	Ratliff et al., (1983).
Transpirable soil water (TSW)	Amount of water available for transpiration at any time, i.e. that amount above the lower limit of extraction. It is (arbitrarily) defined as zero when transpiration is reduced to 10 % of that in the equivalent well watered situation.	Hammer & Muchow (1994)
Total transpirable soil water (TTSW)	The amount of water available for transpiration if the soil is wet to its drained upper limit to the rooting depth of the crop.	Hammer & Muchow (1994)
Fraction transpirable soil water (FTSW)	Ratio TSW/TTSW	Hammer & Muchow (1994)
Field capacity (FC)	The amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased.	Veihmeier & Hendrickson (1931)
Container capacity (CC)	The total percent water, by volume, held by a sample of soil or soil mixture in a container of a given depth with zero hydraulic head at its lower surface, in the absence of evapotranspiration.	White (1964)
	The water content of the potting medium, initially thoroughly wetted, after free drainage from holes in the base of the container ceases.	Cassel & Nielsen (1986)
Permanent wilting point (PWP)	The water content of a soil when indicator plants growing in that soil wilt and fail to recover when placed in a humid chamber.	SSSA (1984); Cassel & Nielsen (1986)
Incipient wilting point (or first permanent wilting point)	The soil water content at which the lowest pair of leaves of a particular kind of plant at a particular growth stage wilts and fails to recover in a water-saturated atmosphere.	Briggs & Shantz (1912), Furr & Reeve (1945)
Wilting range	The range in soil-moisture percentages in which plants undergo progressive permanent, or irreversible, wilting, from wilting of the oldest leaves to complete wilting of all the leaves. The lower end of this range has been termed the ultimate wilting point.	Furr & Reeve (1945)
Available water capacity (AWC)	Amount of water retained in the soil reservoir that can be removed by plants. Estimated as difference between either CC and PWP (for containers) or FC and PWP (for soils).	Cassel & Nielsen (1986)
Readily available soil water (RAW)	That part of total available soil water that can be extracted by plant roots without causing T_a to become less than T_m	
Effective available water (EAW)	Water remaining in a given depth of soil when drainage from that depth ceases + evapotranspiration from that depth until the time drainage ceases - unavailable water (1.5 MPa).	Miller & Aarstad (1973)
Apparent available water (AAW)	Difference between the amount of soil water retained after winter drainage and water content at -1.5 MPa, over rooting depth.	Cabelguenne & Debaeke, 1998.

influence of impeding layers (e.g. argillic B horizon, plough pan, sandy layers) on the matric potential at FC of overlying layers. Others (e.g. Sykes & Loomis, 1967; Driessen, 1995), maintain that the very concept of field capacity is misleading, because a true equilibrium will never be reached in freely draining soils and because soil water above FC, during the first day(s) after irrigation or heavy rainfall, is certainly available to plants.

The lower limit of available soil water is often referred to as permanent wilting point (PWP, table 8.1). The soil water status at PWP depends on the relations between θ, K and ψ, the contact between root surface and soil moisture, evaporative demand of the atmosphere and crop characteristics (Furr & Reeve, 1945; Gardner & Nieman, 1964; Sykes & Loomis, 1967). The soil water content[1)] θ_{pwp} is often associated with $\theta_{-1.5\ MPa}$, the water retained at a matric potential of -1.5 MPa as determined in the laboratory following Richards & Weaver (1943); but values ranging from -3.7 to > -1.0 MPa have been reported (Cassel & Nielssen, 1986; Rawlins et al., 1968). In most soils this variation is not a serious drawback for estimating θ_{pwp}, because the change in water content is very small over this range in matric potential (i.e. $d\theta/d\psi$ is close to zero). However, Ratliff et al. (1983) found that laboratory determinations of $\theta_{-1.5\ MPa}$ were significantly less than field lower limits (LOL, see definition in table 8.1) for sands, silt loams and sandy clay loams and significantly more for loams, silty clays and clays. Cabelguenne & Debaeke (1998) concluded, on the basis of field experiments on an alluvial soil in southern France, that $\theta_{-1.5MPa}$ underestimates the amount of water that can be extracted from surface layers and overestimates the extractable water from the deeper rooting zone. On the other hand, Savage et al. (1996) suggested that the choice of $\theta_{-1.5MPa}$ is appropriate and that discrepancies between $\theta_{-1.5MPa}$ and LOL are mainly due to the treatment of the soil between field sampling and laboratory measurements.

Field capacity and permanent wilting point, when presented as if they were soil constants, together determine the soil's (equally constant) available water capacity (AWC), defined as the difference between FC and PWP over the rooting depth. Some authors also distinguish readily available soil water (RAW) as that part of total available soil water that can be extracted by plant roots without causing actual transpiration rate (T_a) to become less than the maximum transpiration rate (T_m). The latter is a function of evaporative demand of the atmosphere and leaf properties, under optimal soil-water conditions. Ratliff et al. (1983) compared 401 field and laboratory observations on soils from the USA. Results are: (1) average field determined potential extractable soil water (PLEXW, see table 8.1) is not statistically different (5 % significance level) from average laboratory determined (θ_{-33kPa} - $\theta_{-1.5\ MPa}$) for most texture classes, but standard deviations within each texture class are large (average s.d. some 0.03 $cm^3 cm^{-3}$) and (2) PLEXW differences between texture classes, tend to be much smaller then suggested by (θ_{-33kPa} - $\theta_{-1.5\ MPa}$).

8.2.2 The electrical analogue

A common theoretical approach to describe water uptake/transpiration (e.g. Gardner, 1960, Gardner & Ehlig, 1963, Rijtema 1965, Feddes & Rijtema, 1972, Campbell, 1991) uses an electrical analogue, as was first proposed by Gradmann (1928, cited by Van Honert, 1948). This can be represented by the following equation:

$$T_a = U = (\psi_{soil} - \psi_{plant}) / R_{soil+plant} \qquad (8.1)$$

Where

U is rate of water uptake from the soil (e.g. cm day^{-1});

ψ_{soil} is water potential in the soil (e.g. kPa ≈ J kg^{-1}, for water);

ψ_{plant} is water potential in the plant (same units as ψ_{soil});

$R_{soil+plant}$ is resistance to water movement over the distance of flow in the soil and the plant (e.g. kPa cm^{-1} day);

In spite of its apparent simplicity, equation (8.1) is extremely difficult to solve. Variables ψ_{plant}, U, T_a and $R_{soil+plant}$ are interdependent, cannot be controlled and are difficult (often impossible) to measure. $R_{soil+plant}$ represents in fact a complex system of resistances both in series and in parallel, that vary with depth in the soil and in time in soil and plant, according to dynamics of atmosphere, root, water and soil. The following approaches have been tried out to tackle these difficulties:

- break the system down into smaller components (e.g. single roots, soil compartments) that are described separately and then integrated into one model;
- use 'transfer functions' that relate variables that are difficult to assess to more easily measured system parameters;
- consider only the factor(s) that, presumably, limit transpiration and water uptake most.

The first approach, often referred to as microscopic approach (e.g. Hillel et al., 1975; Campbell, 1991, De Jong van Lier & Libardi, 1997; Heinen & de Willigen, 1998) may eventually result in theoretically sound models, that give a detailed description of water uptake from each part of the soil. However, apart from the fact that some of the underlying assumptions of published theoretical models are questionable (for details see Taylor & Klepper, 1975; Tinker, 1976; Sinclair & Ludlow, 1985; Gollan et al., 1986; Zhang & Davies, 1989; Passioura & Stirzaker, 1993), data requirements are prohibitive for application in summary crop growth models.

8.2.3 Simplifications of the electrical analogue

Gardner (1960, 1964) suggested that the resistance term, $R_{soil+plant}$, in equation (8.1) is composed of independent soil and plant resistances (R_{soil} and R_{plant}) that operate in series, and that R_{soil} is conditioned by root system geometry and hydraulic conductivity of the rooted soil. For a soil that is uniformly rooted, this results in:

$$R_{soil+plant} = R_{soil} + R_{plant} \quad (8.2)$$

$$R_{soil} = b(z)/K(\theta) \quad (8.3)$$

where,

$K(\theta)$ is soil hydraulic conductivity [e.g. $(cm\,day^{-1})/(kPa\,cm^{-1})$] as a function of θ;

z is depth below the soil surface (cm);

$b(z)$ is a factor with dimension length (e.g. cm) that takes account of the length and geometry of water flow to the root system, which varies with z.

Assuming continuity (i.e. $U = T_a$), means that ψ_{plant} of equation (8.1), can be taken anywhere in the plant, for example at the base of the stem (crown), where roots converge (e.g. Hillel et al., 1976; Campbell, 1991) or in the leaves (Gardner & Ehlig, 1963, Feddes & Rijtema, 1972, Rijtema & Aboukhaled, 1975; Driessen & Konijn, 1992). In the latter case, R_{plant} represents resistances in series across root membranes, through xylem vessels of roots and stems and into the intercellular spaces within the leaves.

Several studies (e.g.Gardner & Ehlig, 1962; Bristow et al., 1984) indicate that, when the soil is relatively moist, R_{soil} is very small compared with R_{plant}. In this situation there is adequate soil water supply to the plant and T_a equals T_m. This notion could simplify the problem into:

1) determine the soil-water status at which water supply can just keep up with evaporative demand of the atmosphere, i.e. $T_a=T_m$, and
2) determine the relation between soil-water status and transpiration when water is not sufficiently available to satisfy evaporative demand, i.e. $T_a<T_m$.

Rijtema & Aboukhaled (1975) applied these simplifications, to provide a "*very crude first approximation*" of the period free of water limitation during irrigation intervals. They combined the FC and PWP concepts with an electrical analogue model, using simple estimates of ψ_{plant}, R_{plant}, ψ_{soil}, b and K of equations (8.1), (8.2) and (8.3) for the rooted soil as a whole. Their results include RAW estimates tabulated for selected crops, soils and maximum evapotranspiration rates. Once RAW is depleted, they assume a linear relation between actual evapotranspiration rate and the remaining amount of available water in the root zone. This method was extended to saline conditions by Roest et al. (1993) in their on-farm water management model FAIDS.

Driessen & Konijn (1992), in their course book on quantified land use system analysis, suggested different simplified methods to estimate ψ_{plant} and R_{plant} and apply equations (8.1), (8.2) and (8.3) whenever calculated $T_a<T_m$. This approach is applied in the PS123 model, under development by Driessen (1997).

Campbell & Diaz (1988) presented another simplified electrical analogue model that incorporates the field capacity and permanent wilting point concepts. R_{soil} is considered negligible, and simple estimates are made for R_{plant}, ψ_{plant} and ψ_{soil} to calculate water uptake from different soil compartments. Limitation of water uptake is accomplished by preventing ψ_{plant} from dropping below soil water potential at permanent wilt. The authors stressed the need for comparison with more complex models and to test their model with different data sets.

8.2.4 Approaches that focus on soil water potential

Taylor & Ashcroft (1972), strongly emphasised the importance of ψ_{soil} as part of the driving force for water uptake by plants. Since ψ_{soil} varies considerably with depth and over time, Taylor (1952a,b) proposed a method of its integration over rooting depth, obtaining $\psi_{soil,int}$, and averaging over time, obtaining a single "representative" variable, called mean integrated soil moisture potential, $\psi_{soil,int,mean}$. Studies with varying irrigation interval show a strong correlation between $\psi_{soil,int,mean}$ and crop yield (Taylor & Ashcroft, 1972, p. 420-430). Relatively little research has been devoted to the determination of critical values of $\psi_{soil,int}$, i.e. where water uptake starts to lag behind its maximum value. Values suggested for several crops by Taylor & Ashcroft (1972, p. 434) are mostly in the range -100 to -40 kPa during the vegetative stage. Feddes (1969) provided a list of critical ψ_{soil} values, derived from literature, mostly for horticultural crops (−50 to −16 kPa) and fruit trees (−1600 kPa). Gardner & Ehlig (1963) reported much lower critical ψ_{soil} values for pepper, cotton and birdsfoot trefoil: in the range −500 to -100 kPa. Gardner (1983, 1991) suggests that in general, water extraction from the surface soil seems not to decrease before a soil water potential of −1 MPa to −100 kPa is reached.

Crop models that use simple functions of ψ_{soil} to estimate soil water uptake include SWACROP (e.g. Feddes et al., 1978, Van den Broek & Kabat, 1995) and its follow-up SWAP (Van Dam et al., 1997). When ψ_{soil} in a certain layer decreases below a critical value, water uptake from that layer starts decreasing linearly with decreasing ψ_{soil} (their graphical representations invariably suggest log-linear relations), and becomes nil at $\psi_{soil} = \psi_{pwp}$.

8.2.5 Approaches that focus on (relative) soil water content

Gardner & Ehlig (1963) monitored root water uptake from initially wet soils in containers. They found that, as soon as T_a drops below T_m, T_a decreases roughly in proportion with average soil-water content. They explain this by an approximately exponential relation between K and θ, which turns out to yield an approximately linear relation between U and θ over the ψ_{soil} range of interest. Similar results were obtained by Gollan et al (1986) who conducted a laboratory study on wheat and sunflower plants; and by Rawlins et al. (1968) who studied pepper plants in 130 cm deep containers. Bristow et al. (1984), reported that water uptake by sunflowers on several soil types was hardly affected by soil water content as long as θ remained greater than about 25% of the soil's total pore space. Continued drying of the soil resulted in a very sharp decrease of water uptake, that could not be explained by their electrical analogue model. They surmise that entry resistance at the soil/root interface may be a crucial factor in controlling the water supply to plants in dry soil. This resistance is not properly accounted for by either R_{plant} or R_{soil}. Simmonds & Kuruppuarachchi, (1995) substantially improved the accuracy of calculated transpiration rate of a potato crop on sandy loam soil by considering a decoupling of the roots from the soil mass, whenever θ fell below 25 % of the total pore space of the soil.

Irrigation engineers have a long tradition of expressing the amount of readily available soil water (RAW) as a fraction of the maximum amount of plant available water (AWC, PLEXW, TTSW or EAW of table 8.1). This fraction is known as the soil water depletion fraction, *p*. Thompson (1976) reported *p* values between 0.59 and 0.72 for sugarcane, based on field measurements in South Africa and Hawaii, but a study on sugarcane grown in containers (90 cm deep; 24.5 cm ∅) by Nable et al. (1999) suggests a *p* of 0.15. Tyagi et al. (1993) reported a *p* value of 0.25 (for cotton and/or wheat) in northwest India; whereas Smith (1993) implicitly assumes that *p* is 0.8. This value corresponds well with the findings of Ritchie (1973), with maize, and Van Bavel (1967), with alfalfa. Sinclair et al. (1998), based on a literature review and personal experience, reported a "general" *p* value of 0.7 to 0.75, but mentioned ambiguous results for sandy soils.

Once readily available soil water has been depleted, a linear relation between (remaining) available soil water and T_a/T_m, as used in CROPWAT (Smith, 1992), often seems appropriate. Figure 8.1 shows that very similar continuous relations between T_a/T_m and θ can be obtained by logistic equations over the entire range of available water, as suggested by Sinclair & Ludlow (1986) and Hammer & Muchow (1994). The non-linear non-continuous relation used in the EPIC crop growth model (Williams et al., 1989) is also drawn in figure 8.1.

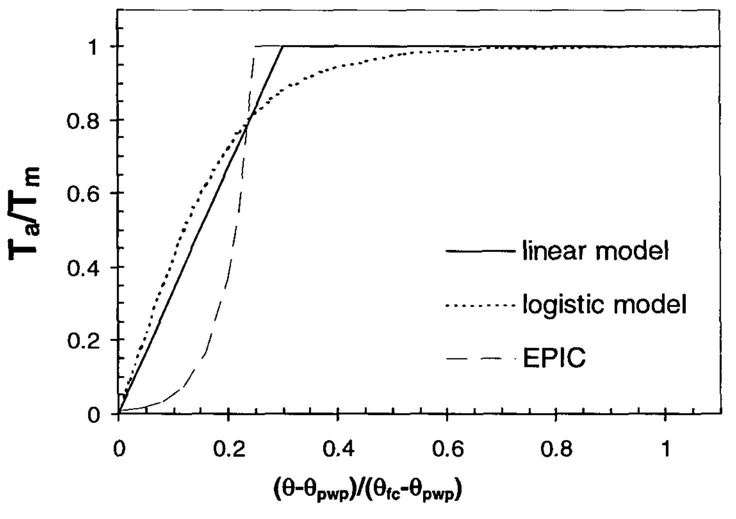


Figure 8.1 Simple approaches to describe T_a/T_m as a function of actually available soil water in relation to AWC

8.2.6 Approaches with special attention to evaporative demand of the atmosphere

Evidently, T_a starts to lag behind T_m sooner when T_m is high than when T_m is small. Denmead & Shaw (1962), who grew maize in containers (60 cm high; 45 cm ∅), found a sharp decrease of T_a/T_m at -30 kPa with T_m = 6.4 mm day^{-1} whereas T_a became less than T_m only at -700 kPa with T_m = 1.4 mm day^{-1}. These values suggest that only some 10% of the total available water was readily available to plants at T_m = 6.4 mm day^{-1} and some 90% at T_m = 1.4 mm day^{-1}. These results had great impact on contemporary thoughts on plant-water relations. [see e.g. Gregory, 1988; Bailey & Spackman (1996)]. However, much less pronounced trends are suggested by results of Yang & de Jong (1972) for wheat plants in small containers (18 cm high; 14.5 cm ∅) and by Hillel et al. (1975), Rijtema & Aboukhaled (1975) and De Jong van Lier (1997) in exercises with theoretical models. Ritchie (1973), with maize and Van Bavel (1967) with alfalfa, did not detect any influence of atmospheric demand on experiments with large lysimeters in cropped fields. Bunce (1989) however, concludes from a review of experiments with soybeans that water stress around midday is *"an almost everyday phenomenon"*, even on moist soils.

Doorenbos & Kassam (1979), proposed a simple method to calculate irrigation requirements, considering the relation between actual evapotranspiration rate (ET_a) and maximum evapotranspiration rate (ET_m). Tabulated indicative *p*-values are provided for 'crop groups' and several levels of ET_m. Whenever water depletion exceeds *p*, they let ET_a/ET_m decrease proportionally to the remaining amount of available soil water. According to Doorenbos (personal communication, 1999) these *p* values are based on the previously mentioned simplified electrical analogue model of Rijtema & Aboukhaled (1975), supplemented with a considerable dosage of expert judgement from experienced irrigation engineers. Doorenbos and Kassam (1979, p. 28) stressed the need to validate the approach and to compare the results with results obtained with other methods. The approach is used in several crop growth and irrigation management models, e.g. WOFOST (Boogaard et al., 1998) and BIDRICO 2 (Danuso et al., 1993). It was updated by Allen et al. (1998) with a more detailed list of reference *p* values and less influence of ET_m on *p*.

8.2.7 Approaches with special attention to non-uniform water uptake

The exact distribution of available water in a soil is of minor importance to the users of summary crop growth models. However, this aspect may not be ignored altogether if water contents vary considerably within the rooted soil. This is not uncommon in soils with a shallow ground water table, and in dry fields that receive occasional inputs of rainfall (or irrigation) that are insufficient to wet the entire root zone. In such situations (which are clearly within the scope of the biophysical assessment of land use systems) it may be unrealistic to consider average water status of the entire root zone (c.f. Ritchie, 1981, p. 92). It would be expected – and process based theoretical models predict - that limited water uptake from dry zones is (partly) compensated by increased water uptake from sites where it is readily available. Actual data providing experimental evidence on compensatory effects are scarce. Results with soybeans published by Reicosky et al. (1972) suggest that, in the presence of a water table, 20 % of the root system (on dry weight basis) can be responsible for 94 % of the water uptake. The soybean crop of their study was adapted to the specific conditions and root density showed a bulge just above the groundwater. On the other hand, Rawlins et al. (1968) conducted a container study on the effect of surface irrigation on transpiration of a pepper plant (*Capsicum frutescens* L.). They found a strong correlation between transpiration and total amount of soil water, regardless of its distribution.

A logical consequence of accepting the need to account for compensatory effects, by keeping track of water dynamics at several soil depths, is that attention should also be given to the vertical distribution of water uptake when soil water is uniformly distributed. Gardner (1983, p. 58-60) reviewed a large number of experiments with different soil-crop-atmosphere combinations. He plotted observations of normalised cumulative water uptake from the soil - until the moment that T_a started to lag behind T_m - vs. normalised depth. The resulting graph, (figure 8.2) in general confirms the rule of thumb shared by generations of irrigation engineers that 40, 30, 20 and 10 percent of total water uptake comes from successively deeper quarters of the root zone.

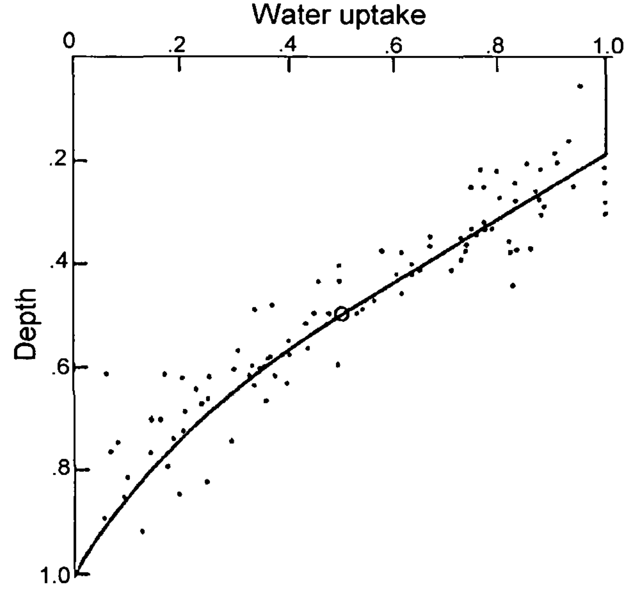


Figure 8.2 Normalised water uptake curves for some 40 different experiments. Data for day of first wilt, as estimated. Source: Gardner (1983)

Based on these and other results, Gardner (1983, p. 57) stated: *"... starting with a uniformly wet soil profile, water is initially extracted from the region nearest the surface, with the zone of extraction progressing downward through the profile...."* and *"Whenever the soil water near the surface is replenished by precipitation or irrigation, the extraction zone goes back to the surface and moves downward again"*.

Several models claim to account for preferential water uptake from wet parts or surface layers of the soil, or both. These models have in common that they divide the rooted surface layer into vertical compartments, usually with thickness between 5 and 50 cm. A few examples are given below.

Van Keulen & Seligman (1987, p. 98-99) presented a growth model of spring wheat, in which they assign a "root activity coefficient" to each compartment that is a function of the compartment's moisture content. In this way, they account for increased water uptake from moist compartments if water distribution is not uniform. Van Keulen et al. (1997) and Stroosnijder & Kiepe (1998), combined this procedure with the approach of Doorenbos & Kassam (1979). Their models calculate uniform water uptake when water is uniformly distributed in the soil.

Hoogland et al. (1981), proposed a root water uptake model that accounts for both compensatory effects and a shift in time of maximum water extraction from the surface downward:

$$S(z,\psi) = \alpha(\psi).S_{max}(z) \tag{8.4}$$

where,

- S is the sink term ($cm^3\,cm^{-3}\,day^{-1}$), i.e. the rate of water uptake per unit soil volume from a compartment at depth z (cm),
- $\alpha(\psi)$ is a dimensionless reduction factor ($0 \leq \alpha \leq 1$) that is a function of the soil water potential in the compartment,
- $S_{max}(z)$ is a depth-dependent maximum value of S ($cm^3\,cm^{-3}\,day^{-1}$).

For S_{max}, they suggest a linear relation with z, of type

$$S_{max} = a - c.z \tag{8.5}$$

where a and c are constants.

Based on literature data, they postulated $0.01 \leq a \leq 0.03$ $cm^3\,cm^{-3}\,day^{-1}$ as a first estimate, but the values of c appeared to be inconsistent. Water uptake from upper layers is favoured by integrating S from the surface downwards until either $U=T_m$, or the bottom of the root zone is reached at $U < T_m$. Prasad (1988), adapted this model by proposing to vary parameters a and c each time step, j, in such a way that $\int_{z=0,D_r} (S_{max})dz = T_{max,j}$ and $S_{max} = 0$ at depth D_r (the bottom of the rooted soil). This approach can be selected as an option in the SWACROP model as used by Leummens et al. (1995).

The EPIC crop growth model (Williams et al., 1989) uses a non-linear relation of S_{max} against depth, which is corrected for a root-growth-stress dependent water deficit compensation factor to indicate the degree of compensation between layers. The result is multiplied with the soil-water-content-dependent reduction factor of figure 8.1, to calculate water uptake from each soil compartment. Cabelguenne & Debaeke (1998) expanded this procedure by adding an empirical relation to account for depth dependent maximum soil water depletion.

Ghali (1986, cited by Kabat & Feddes, 1995) introduced a radical mechanistic approach, based on a concept of *"minimisation of work to be done by plants"*. This would also be accomplished by extracting greater volumes of water from wetter soil compartments.

8.3 Discussion

Controversy with respect to water availability is as old as soil physics (c.f. e.g. Veihmeyer & Hendrickson, 1955; Gardner, 1968). Major causes of this are (1) the way in which spatially and temporally variable data are treated (transformed to mean, average or integrated values); (2) dogmatic adherence to - and indiscriminate application of - pragmatic choices suggested in the past, and (3) lack of field testing of results obtained in greenhouse conditions or generated by computer models.

8.3.1 Upper and lower limits of available soil water and readily available soil water

Most simple water uptake models rely on the concepts of field capacity, permanent wilting point and available water capacity, or similar ones as listed in table 8.1. These concepts have a weak basis because they disregard the dynamic nature of water availability. Their persistence is explained by the lack of practical alternatives and the relative abundance of available data (e.g. USDA, 1964, Batjes, 1996; Van den Berg et al., 1997). Field capacity seems most problematic but errors incurred with its use can be assessed by field determinations. These are labour intensive, but require no sophisticated equipment or particularly skilled staff. After analysis of field determinations one can decide if its use is acceptable for the specific situation and type of application and if laboratory data can be used as a surrogate. Determination of PWP (or LOL) is more difficult, but using $\theta_{-1.5MPa}$ seems acceptable in many conditions. The discrepancy between field measurements and $\theta_{-1.5MPa}$ reported by Cabelguenne & Debaeke (1998) may at least partly be explained by the combined action of evaporation and root water uptake in surface soil layers. Deep rooted layers remained relatively unaffected in their study, possibly because permanent wilting was never attained. Field-testing is certainly necessary on specific soil types, with large $d\theta/d\psi$ in the dry range and soils of the tropics (e.g. Ferralsols), for which very few or no data are available.

8.3.2 Simplifications of the electrical analogue

Simplified theoretical models have their own merits, e.g. for educational purposes or for practical assessments if they are properly tested in their range of application. However, these models rely heavily on the use of default parameters, usually obtained by regression with a very weak experimental support. Using such models for analytical purposes (e.g. assessment of land-use systems) may give unreliable results if they are not properly tested and/or surrogate input data are used. Users of the model proposed by Campbell & Diaz (1988), should be aware that R_{soil} is assumed of negligible importance in their electrical analogue representation. This means implicitly that they do not consider the soil's hydraulic conductivity (K). Others consider K the principal factor that governs water uptake from dry soils. Average or integrated ψ_{soil}, R_{soil} or K values for entire root zones may correlate well with crop water uptake when the starting point is a uniform deep wetted soil. However, the physical meaning of such "representative" variables is questionable in quantitative description of soil water processes, because the real values of ψ_{soil}, and K may vary by several orders of magnitude within the rooted soil, especially when wet and dry zones occur side by side.

8.3.3 Approaches that focus on soil water potential vs. approaches that focus on (relative) soil water content

The disagreement on the critical soil water potential that marks the lower limit of readily available soil water may not be what it seems. The values suggested by Taylor and Ashcroft (1972, p. 434), typically in the range -100 to -50 kPa, were either obtained by integration over the entire rooting depth, or by transformation from water depletion fractions over the entire rooting depth; or refer to observations below the depth of maximum root concentration. Critical values mentioned by Feddes (1969), in the range from –50 to –16 kPa, apparently refer to the soil water potential halfway the maximum rooting depth of horticultural crops that are very sensitive to water shortage. The critical values in the range -1000 to –100 kPa mentioned by Gardner (1983) refer to the surface soil and typically to grain crops.

Arguments intended to support the choice of a critical ψ_{soil} (and not e.g. soil water depletion fraction) to indicate the lower limit of readily available soil water (see e.g. Taylor & Ashcroft, 1972, p. 432; Kabat & Feddes, 1995, p. 114) show that different calculation methods yield different estimates of RAW. However, they fail to prove that one method is better than the other. If water uptake is affected at ψ_{soil} of -100 to -50 kPa, this is caused by the small value of K and root/soil/water interface relations, rather than by direct influence of ψ_{soil} which, by itself (as component of the driving force for water uptake), is far too high to be important in reducing flow rates. There is no experimental evidence that ψ_{soil} vs. T_a/T_m relations are more consistent than relations between soil water depletion and T_a/T_m. Several of the critical $\psi_{soil,int}$ values suggested by Taylor & Ashcroft (1972) were obtained by conversion from soil water depletion fractions! Many others refer to unpublished works. The fact that the same sources are repeated over and over suggests a weak experimental basis of indicative values. For example, Feddes et al

(1976) mention a value of some –40 kPa for vegetable crops, citing Feddes (1971), who refers to Feddes (1969). Critical ψ_{soil} values listed in the SWAP document (Van Dam et al., 1997, p. 155-156) are those of Taylor & Ashcroft (1972) and the ones that were chosen (i.e. not determined) by Wesseling (1991). Homaee (1999), studied water uptake by alfalfa in containers and proposed a two-piece linear fit of experimental T_a/T_m as function of mean ψ_{soil}. Comparison of this relation with his figure 5.4 suggests that a linear fit of T_a/T_m as function of mean soil water content could have been selected just as well.

Using a soil water depletion fraction (p) to indicate the lower limit of readily available soil water also presents flaws. Published values are often not comparable because the definition of p depends on the methods used to determine the limits of water availability, which are not uniformly defined. Proliferation of terms as listed in table 8.1, and their indiscriminate use have perhaps contributed more to mystification than to clarification of the problems involved. Sinclair et al. (1998) found apparently more consistent p's when the upper limit of water availability for container grown soybean on sandy soils was defined as container (pot) capacity (c.f. table 8.1) than as θ_{-10kPa}! Rehashing the words of Sinclair & Ludlow (1985): who taught plants to calculate the water storage capacity of the potting medium?

8.3.4 The role of evaporative demand of the atmosphere

The reasons for discrepancies with respect to the influence of evaporative demand on T_a/T_m are not entirely clear. Ritchie (1981) provides several examples to illustrate that results obtained in small containers are not representative for field conditions. The rate of soil water depletion is much greater in small containers with large plants, as used by Denmead & Shaw (1962), than in the field where a large soil volume is explored. In the former conditions, plants may have no time to adapt by osmotic adjustment. The choice of a reference for T_m seems of special importance with respect to the influence of midday peak evaporative demand on crop growth, as reported by Bunce (1989). This influence is not easily detected when well-watered plants are taken as the reference, which is usually the case.

8.3.5 Approaches with special attention to non-uniform water uptake

Non-uniform water uptake and the possible influence of non-uniform soil water distribution on T_a/T_m, cannot be modelled without subdividing the rooted soil into compartments. The appropriate thickness of compartments can be inferred from sensitivity analyses. Intuitively, a thickness of more than 20-25 cm seems too rough.

Some of the models discussed use a depth dependent maximum sink term to account for non-uniform water uptake (equations 8.4 and 8.5). Results of Gardner (1983) suggest that a depth dependent $\alpha(\psi)$, or $\alpha(\theta)$, in analogy with figure 8.2, may be more appropriate. A depth dependent maximum sink term for soils with high groundwater level seems tricky. The root system will tend to adapt itself and water withdrawal from a small zone just above the groundwater level may be sufficient to satisfy the evaporative demand, as was shown by Reicosky et al., 1972. The concept of minimisation of work to be done by plants (Ghali, 1986) as described by Kabat & Feddes, 1995) either overlooks some basic aspects of physics or uses a confusing vocabulary. Plant water uptake is basically a passive process. The "work" required to be done by plants is to grow roots were water is available and, possibly, to open and close stomata; not to grasp the water from the soil.

The model presented by Cabelguenne & Debaeke (1998) seems to be the one that was most seriously tested for several crops under irrigated and non-irrigated conditions; but only for Mediterranean climate and one type of layered alluvial soil. Their method to estimate crop water uptake, using four parameters and several depth dependent equations, seems rather speculative. A simpler approach could perhaps give equally good fits for more homogeneous soils.

8.3.6 Closing remarks

The analysis of different applications suggests that procedures are too easily accepted and passed on. This is illustrated with a few examples.

The model for nation wide (UK) irrigation scheduling of Bailey & Spackman (1996) incorporates a relationship calibrated to fit closely to the data of Denmead & Shaw (1962), which were never reproduced under field conditions.

Rijtema & Aboukhaled (1975) used their simplified electrical analogue model as a "*very crude first approximation*" to calculate the amount of soil water (as a proportion of the water retained between -1.6 MP and -10 kPa), that can be withdrawn from an initially wet soil before $ET_a<ET_m$. The method assumes a well developed root system and closed crop canopy. Their results seem practically soil-independent, but their descriptive equation for the relation $K(\psi)$ in the dry range is derived from a small data set of mostly alluvial soils with mixed mineralogy (Rijtema, 1965). The results of Rijtema & Aboukhaled (1975) formed the basis for the tabulated soil water depletion fractions, *p*, of Doorenbos & Kassam (1979), who expressed *p* as a proportion of water retained between -1.5MPa (or PWP) and -20 to -10 kPa (or FC). Boogaard et al. (1998) adopted this method to calculate T_a/T_m, in situations with or without irrigation and/or influence of groundwater, irrespective of root and canopy development. Their *p* values (numerically identical to those of Doorenbos c.s.) are expressed as a proportion of (θ_{fc} - θ_{pwp}). Van Keulen et al., (1997) and Stroosnijder & Kiepe (1998) combined this approach, with slightly different *p* values, with a procedure of Van Keulen & Seligman (1987), to account for compensatory effects in soils with non-uniform water distribution.

Subsequent adaptations without proper testing lead to distortions. Evapotranspiration is obviously not the same as transpiration. Considerable differences occur when crop canopies are not closed. Furthermore, the simple models examined ignore the fact that during initial development soil water below plant rows is more easily accessible than water stored between rows. The models will therefore exaggerate the beneficial effect of wide spacing, which is a common management measure in semi-arid environments.

Summarising, there is no evidence that any of the reviewed methods is suitable for application to a broad spectrum of environments. None of the methods was seriously tested over a wide range of dry land conditions. A simple approach, estimating T_a/T_m as a function of soil water contents seems most indicated, but uncertainties remain with respect to the assessment of critical soil water contents and the true importance of compensatory effects. The consequences of such uncertainties, which can only be reduced by elaborate field studies on different kinds of weather-soil-crop conditions, could be quantified by means of numerical analysis using ranges of possible values and scenarios for different environments.

8.4 Conclusions

1. Discrepancies between crop water uptake descriptions stem mainly from different interpretations of averaged or generalised data, and the dogmatic adherence to - and indiscriminate application of - pragmatic choices suggested in the past.

2. Models that perform calculations on the rooted soil as a whole seem inappropriate for dynamic modelling of water uptake in soils that are subject to irregular cycles of drying and wetting with varying amounts of water.

3. Simplified theoretical descriptions are well suited for educational purposes or for practical assessments if they are properly tested throughout their range of application, but there is no convincing evidence that theoretical water uptake models using default parameter values and/or surrogate input data (e.g. roughly estimated or extrapolated K-θ relations) are better suited for practical application than simple empirical models with modest data input requirements.

4. Preference for any single soil water status variable to indicate readily available soil water should be based on practical implications (e.g. data availability). Theoretically, both (relative) soil water content and ψ_{soil} have some direct influence on water uptake and they are strongly related.

5. There is a great need for reliable data sets for further development and testing of models of crop water uptake in rain fed field conditions, especially in the tropics.

[1)] According to current definitions (table 8.1), FC is defined as an amount of water over a certain soil depth, whereas PWP is defined as a soil water content. For reasons of uniformity, in this text, the soil water contents (volume fraction) are indicated by respectively θ_{fc} and θ_{pwp}.

9. WATER UPTAKE IN SUMMARY CROP GROWTH MODELS. II. COMPARISON OF THREE SIMPLE APPROACHES

9.1 Introduction

As mentioned in chapter 8, most so-called summary crop growth models include simplified descriptions of water loss by transpiration from leaves and subsequent water uptake through roots and the consequences thereof for crop growth. A linear relation between the rates of transpiration and photosynthesis is often suggested (e.g. Van Keulen & van Laar, 1986; Penning de Vries et al., 1989):

$$P_g = P_{max} * TR_a/TR_m \qquad (9.1)$$

where,

P_g is gross assimilation rate (e.g. kg CO_2 m^{-2} day^{-1});
P_{max} is maximum gross assimilation rate, a function of radiation, temperature and crop phenology under optimal soil-water conditions (same units as P_g).
TR_a is actual transpiration rate (e.g. cm day^{-1});
TR_m is maximum transpiration rate, a function of evaporative demand and leaf properties, under optimal soil-water conditions (same units as TR_a);

Clearly it appears essential to be able to compute TR_a/TR_m reliably over a wide range of conditions. The review in chapter 8 of simple approaches to calculate TR_a/TR_m and their pedigrees however revealed many discrepancies. The most important differences affecting the outcome of equation 9.1 can be summarised as:

- The algorithms are either simplifications of complex flow models or are based on observed (or inferred) relations between TR_a/TR_m and other environmental characteristics.
- Different methods are used to handle water uptake from soils with non-uniform water distribution.
- Different methods are used to handle non-uniform soil water uptake from soils with uniform water distribution.
- Different variables are used to indicate the limit of so-called readily available soil water (i.e. that part of total available soil water that can be extracted by roots without causing TR_a to become less than TR_m). The most popular criteria used are (1) "soil water depletion fraction" (e.g. Doorenbos & Kassam, 1979) and (2) soil water potential (e.g. Feddes et al., 1978). Disparate critical values of these variables are found in the literature.

Chapter 8 concluded that conceptual differences stem mainly from different interpretations of averaged or generalised soil water data, and the indiscriminate use of pragmatic ad-hoc choices suggested in the past. No records were found that suggest that any of the models had been tested well under a variety of rain fed field conditions.

However, flaws in the description of crop water uptake do not necessarily imply an unsatisfactory performance of summary crop growth models. Users are mainly interested in the relation between TR_a and TR_m over time and less in the exact spatial and temporal distribution of water uptake from the soil. One could argue that, on a day by day basis, errors incurred by (over)simplification are partly corrected through negative feedback: when calculated transpiration at day i is too high, water content of the soil at the end of day i will be too small, resulting in less transpiration at day i+1 (Hoogland et al., 1981). Results of Alaerts et al. (1985) seem to support this idea. They compared four water uptake models with different degrees of complexity. Calculated cumulative water losses over a period of 20 days were similar, if input data and parameter values were adjusted, even though daily water extraction depth patterns were considerably different.

The objectives of this chapter are (1) to test the hypothesis that the way water uptake is simulated is of minor importance for summary crop growth models and (2) to identify constraints and suggest improvements when appropriate.

To accomplish this, estimates of TR_a computed by three different methods were compared. The different methods are used in the WOFOST (Boogaard et al., 1998), SUCROS2 97 (Van Keulen et al., 1997) and PS123 (Driessen, 1997) models. This chapter does not address the calculation of TR_m, and considers only the effects of water shortage, and not the effects of excess water in soil or soil salinity on water uptake and crop growth.

The chapter is organised as follows. Section 9.2 describes the algorithms for water uptake and the effects of water shortage on crop growth in the compared models. Section 9.3 describes the exercises for model comparison that were carried out in this study. The results of the exercises are presented in section 9.4 and discussed in section 9.5. Suggestions for improvement are given in section 9.6, and the conclusions are presented in section 9.7.

9.2 Models compared in this study

Dimensions, notations and acronyms used in publications referred to in this chapter have been standardised and units adapted to SI norms. Symbols used are listed in table 9.1. Table 9.2 lists the main features of the models compared in this study.

<u>WOFOST</u>

A detailed system description of the WOFOST model, version 6.0, is given by Supit et al., (1994). The algorithm for crop water uptake remained unchanged in the 7.1 version (Boogaard et al. 1998). One single compartment represents the entire root zone. The lower boundary of this compartment moves downward as rooting depth increases over time. The reduction of water uptake due to water stress, f_r ($\equiv TR_a/TR_m$), is based on

Table 9.1 Symbols used throughout this text

Symbol	Description	Units
$\psi_{leaf,c}$	critical leaf water potential, i.e. leaf water potential just before stomatal closure;	kPa
ψ_{plant}	water potential in the plant;	kPa
ψ_{soil}	soil water potential;	kPa
Θ_r	"relative available water content", i.e. soil water content expressed as fraction of available water capacity: $\Theta_r = (\theta - \theta_{wp}) / (\theta_{fc} - \theta_{wp})$;	-
θ	soil water content;	$cm^3\ cm^{-3}$
θ_{fc}	soil water content at "field capacity";	$cm^3\ cm^{-3}$
θ_{pwp}	soil water content a permanent wilt ("permanent wilting point");	$cm^3\ cm^{-3}$
c_r	"root activity coefficient" , conditioned by soil water content in SUCROS model (c.f. equation 9.5 and figure 9.2);	-
D_j	depth of lower boundary of compartment *j*;	cm
$D_{r,e}$	effective rooting depth;	cm
$D_{r,j}$	thickness of the rooted part of soil compartment *j* (c.f. equation 9.5);	cm
ET_m	maximum evapotranspiration rate (as conditioned by crop characteristics, leaf area index and atmospheric conditions);	cm^{-1} day
f_r	relation between actual transpiration rate and maximum transpiration rate (TR_a/TR_m);	-
$f_{r,j}$	reduction factor to determine relation between actual water uptake rate and maximum water uptake rate from soil compartment *j* (c.f. equation 9.7);	-
K	soil hydraulic conductivity;	$cm^2\ day^{-1}\ kPa^{-1}$
p	soil water depletion fraction, i.e. the proportion of the total available soil water over the root depth that can be depleted without causing ET_a to become less than ET_m;	-
P_g	gross photosynthesis rate;	kg $CO_2\ m^{-2}\ day^{-1}$
P_{max}	maximum gross photosynthesis rate, which is a function of radiation, temperature and crop phenology under optimal soil-water conditions;	kg $CO_2\ m^{-2}\ day^{-1}$
$R_{e,j}$	"effective root length" in soil compartment *j*, conditioned by soil water content in SUCROS model (c.f. equation 9.5);	cm
R_{plant}	resistance to water movement over the distance of flow in the plant;	kPa cm^{-1} day
R_{soil}	resistance to water movement over the distance of flow in the soil;	kPa cm^{-1} day
TR_a	actual transpiration rate;	cm day^{-1}
TR_m	maximum transpiration rate, which is a function of atmospheric demand and leaf properties, under optimal soil-water conditions;	cm day^{-1}
U	root water uptake rate from the soil;	cm day^{-1}
$U_{a,j}$	actual water uptake rate from soil compartment *j* (c.f. equation 9.7);	cm day^{-1}
U_{max}	maximum uptake rate of water from the rooted soil compartment (used in PS123);	cm d^{-1}
U_{rmm}	maximum water uptake rate per unit length effective rooting as used in SUCROS (c.f. equation 9.6);	cm $cm^{-1}\ day^{-1}$
$W_{x,j}$	water in excess of field capacity in soil compartment *j*;	cm
z	Depth below the soil surface;	cm

Table 9.2 Outline of water uptake/transpiration in three crop models

	WOFOST	SUCROS	PS123
Number of compartments in root zone	1	up to 4	1
Lower boundary of deepest compartment follows rooting depth	yes	no	yes
Method to determine if soil water is readily available	Soil water depletion fraction	Soil water depletion fraction in each compartment	Maximum flow rate through soil and plant as related to TR_m
Determination of TR_a/TR_m when soil water is not readily available	Linear function of fraction available water	Linear function of fraction available water, weighted by *"effective root length"* in each compartment	Maximum flow rate through soil and plant

the approach suggested by Doorenbos & Kassam [1979; Supit et al. (1994) actually refer to Doorenbos et al, 1978].

WOFOST defines the available water capacity as the difference between soil water content at field capacity, θ_{fc} ($cm^3 \, cm^{-3}$) and permanent wilting point, θ_{pwp} ($cm^3 \, cm^{-3}$) in the root zone. It is assumed that a fraction p of (θ_{fc} - θ_{pwp}) can be depleted before TR_a drops below TR_m. The critical soil water content, θ_c ($cm^3 \, cm^{-3}$), is given by:

$$\theta_c = \theta_{pwp} + (1-p) * (\theta_{fc} - \theta_{pwp}) \qquad (9.2)$$

The soil water depletion fraction, p, is a function of crop group and maximum evapotranspiration rate (ET_m). The equations used were obtained by multiple regression, using the tabulated values suggested by Doorenbos et al (1978, cited by Supit et al, 1994) for five crop groups (see Appendix 1). TR_a/TR_m becomes nil when water content in the rooted soil, θ($cm^3 \, cm^{-3}$) $\leq \theta_{pwp}$. A linear relation is assumed when $\theta_c > \theta > \theta_{pwp}$. This is illustrated in figure 9.1, where θ is re-scaled to a relative available water content of the rooted zone (Θ_r) i.e. the available soil water expressed as a fraction of (θ_{fc} - θ_{pwp}):

$$\Theta_r = (\theta - \theta_{pwp}) / (\theta_{fc} - \theta_{pwp}) \qquad (9.3)$$

$$TR_a/TR_m \equiv f_r = MAX[0., MIN(1., \Theta_r/(1-p))] \qquad (9.4)$$

WOFOST uses equation (9.1) to calculate the effect of reduced transpiration on photosynthesis. A non-stomatal effect of water stress on crop performance is introduced through an increased death rate of leaves.

The modest data needs are a strong feature of the approach. Apparently weak points are: (1) the method ignores possible effects of irregular water distribution in the root zone; (2) the lack of theoretical or experimental evidence for general applicability of the generated p values; (3) relations and parameters originally meant for

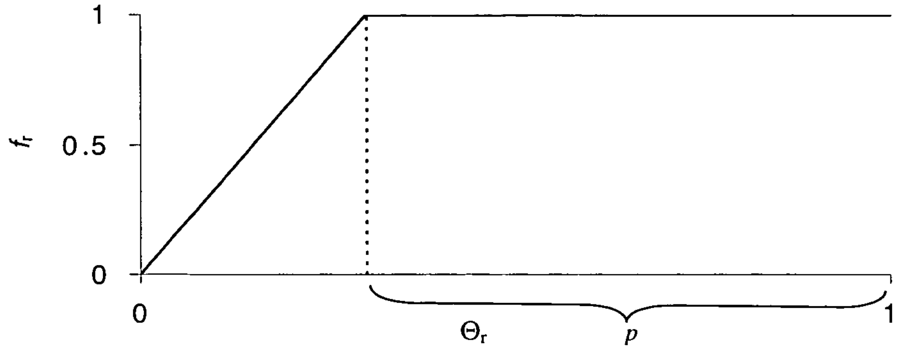


Figure 9.1 Relative transpiration rate (f_r = TR_a/TR_m) as a function of "relative available water content" (Θ_r) and soil water depletion fraction p

evapotranspiration under irrigated conditions (Doorenbos & Kassam, 1979) are used to calculate transpiration under any condition.

SUCROS

SUCROS2-97 (Van Keulen et al., 1997) divides the soil into horizontal compartments having different thickness. Four compartments are considered in the documented example of SUCROS for spring wheat, with fixed lower boundaries at 20, 60, 120 and 200 cm below the soil surface. Calculation of daily water uptake/ transpiration is based on the approach suggested by Doorenbos & Kassam. (1979), in a similar manner as implemented in WOFOST (equations 9.2, 9.3 and 9.4). However, SUCROS calculates p values differently (see Appendix 1 for details) and f_r is calculated separately for each soil compartment j, as $f_{r,j}$. Water uptake from each compartment is calculated using the method of Van Keulen & Seligman (1987, p. 98) to accommodate compensatory effects when water is not homogeneously distributed in the soil:

1. calculate *effective root length*, $R_{e,j}$ (cm), of each compartment j; by multiplying the thickness of the rooted part of the compartment, $D_{r,j}$ (cm) by a *root activity coefficient* c_r:

   $$R_{e,j} = D_{r,j} * c_r \qquad (9.5)$$

   Values of c_r are obtained by linear interpolation between tabulated values of c_r, at specific values of Θ_r. A graphical representation of this function is given in figure 9.2.

2. calculate *cumulative effective rooting*, ΣR_e, by summing $R_{e,j}$ -values of each compartment;

3. calculate *"maximum rate of water uptake per unit length of effective rooted depth"* (U_{rmm}, cm cm^{-1} day^{-1}) as:

$$U_{rmm} = TR_m/\Sigma R_e \qquad (9.6)$$

4. calculate actual water uptake rate from each compartment j ($U_{a,j}$, cm day^{-1}) as:

$$U_{a,j} = f_{r,j} * U_{rmm} * R_{e,j} \qquad (9.7)$$

5. calculate actual transpiration rate TR_a as the sum of $U_{a,j}$ of each soil compartment.

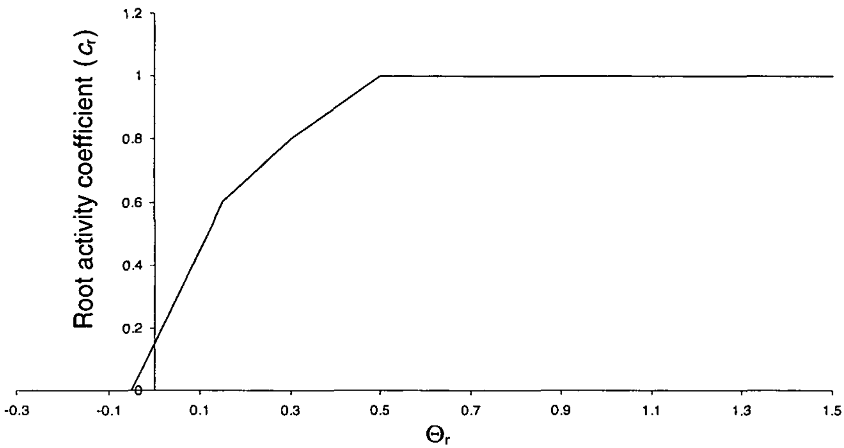


Figure 9.2 SUCROS' Root activity coefficient (c_r) as function of relative available water content (Θ_r)

SUCROS uses equation (9.1) to calculate the effect of reduced transpiration on photosynthesis. Non-stomatal effects of water stress on crop performance are (1) root extension ceases when the root front reaches a soil comportment with $\theta \leq \theta_{pwp}$, and (2) partitioning of assimilates to the roots increases if TR_a/TR_m is less than 0.5. The same approach is used in the MAIZE2 model (Stroosnijder & Kiepe, 1998).

The approach followed by SUCROS has the advantages of (1) modest data needs, and (2) attention for compensatory effects between compartments in case of heterogeneous soil water distribution. Apparently weak points are (1) the lack of evidence that compensatory effects in case of heterogeneous soil water distribution are correctly described; (2) calculated p values seem not universally applicable (e.g. calculated p's are close to 1. in emerging crops); (3) relations and parameters that were meant for evapotranspiration (Doorenbos & Kassam, 1979) are used to calculate transpiration; (4) the model ignores preferential water uptake from the surface compartment(s) in soil with uniform water distribution (see e.g. Gardner, 1983).

PS123

Like WOFOST, the PS123 model treats the rooted surface soil as a single compartment with a shifting lower boundary. The method developed to calculate water supply to the transpiring crop is explained by Driessen & Konijn (1992, p. 92-95). It is a simplification of the electrical analogue approach which is used in many theoretical models (Gardner & Ehlig, 1963, Feddes & Rijtema, 1972, Campbell, 1991, Heinen & de Willigen, 1998).

The maximum rate of water uptake from the soil, U_{max}, (cm d^{-1}) is calculated by:

$$U_{max} = (\psi_{soil} - \psi_{leaf,c}) / (R_{plant} + R_{soil}) \qquad (9.8)$$

where,

ψ_{soil} is soil water potential (kPa);

$\psi_{leaf,c}$ is critical leaf water potential, i.e. the water potential in the leaf that is built up just before stomatal closure. In PS123 this is considered a crop parameter, e.g. approximately −1600 kPa for most grains;

R_{plant} is resistance over the distance of water flow in the plant (kPa cm^{-1} day);

R_{soil} is resistance over the distance of water flow through the soil to the roots (kPa cm^{-1} day).

The actual rate of transpiration, TR_a, is equal to TR_m in the absence of water stress, i.e. when $U_{max} \geq TR_m$, and equal to U_{max} when stress prevails:

$$TR_a = MAX(0., MIN(TR_m, U_{max})) \qquad (9.9)$$

PS123 calculates R_{plant} based on a compilation of published data examined by Reinds (1987). Driessen & Konijn (1992, p. 94) suggest that R_{plant}, although influenced by the crop's physiological development stage and decreasing when the rate of transpiration increases, is for practical purposes a constant that is determined by the physiological tolerance to drought, as expressed by $\psi_{leaf,c}$:

$$R_{plant} = 68 - 0.53 * \psi_{leaf,c} \qquad (9.10)$$

(recall that $\psi_{leaf,c}$ has a negative value)

R_{soil} is approximated according to Feddes & Rijtema (1972):

$$R_{soil} = 13./ (D_{r,e} * K(\theta)) \qquad (9.11)$$

where,

$K(\theta)$ is soil hydraulic conductivity [(cm day^{-1})/(kPa cm^{-1})] as a function of soil water content, θ;

$D_{r,e}$ is effective rooting depth (cm).

Note that parameters 68, 0.53 and 13 of equations (9.10) and (9.11) are not dimensionless!

PS123 calculates the effects of water stress on crop performance by equation (9.1) and considers incoming energy by solar radiation and energy losses through reflection, long-wave radiation, and latent heat of vaporisation from the crop canopy. When transpiration is less than maximum, leaf temperature goes up which results in accelerated respiration, leaf ageing and leaf death.

A strong feature of the PS123 approach is its theoretical foundation. Weaknesses identified by Driessen & Konijn (1992) are that application of the model should be restricted to deep homogeneous non-swelling soils; and the rough estimates of R_{plant}, R_{soil} and ψ_{leaf}. The fact that R_{soil} and ψ_{soil} are treated as "average" values for the entire rooted soil may affect the performance of the model when roots and/or water are not uniformly distributed in the soil. Furthermore, the approach needs data on $\theta(\psi)$ and $K(\theta)$ relations that are difficult to obtain.

9.3 Methods for comparative modelling exercises

Five comparisons were made:

(1) Calculate TR_a over time after wetting the soil over the entire root zone, which is set at 100 cm; TR_m is fixed at 0.5 cm day^{-1};

(2) Calculate TR_a over time after wetting the soil over the entire root zone, which is set at 120 cm; TR_m is fixed at 0.5 cm day^{-1}

(3) Calculate TR_a after infiltration of varying amounts of water in a dry soil (to represent a rain shower or irrigation after a long period of drought); rooting depth is fixed at 100 cm; TR_m fixed at 0.5 cm day^{-1};

(4) Calculate TR_a as a function of rooting depth, D_r, after application of 2.0 cm water to a dry soil; TR_m is fixed at 0.5 cm day^{-1};

(5) Calculate cumulative TR_a over time, with applications of 4.0 cm of water every 8th day; rooting depth is fixed at 120 cm; TR_m is fixed at 0.5 cm day^{-1};

These exercises were carried out using data files from four soils: (1) a clay-loam soil; (2) a sandy soil, (3) SJ7001, a clayey Dusky Red Earth (Rhodic Nitisol) from study field nr.1 of the Araras region, and (4) SJ7010, a clayey Dusky Red Latosol (Rhodic Ferralsol) from study field nr. 2 of the Araras region. Moisture retention curves of the four soils and graphical representations of the $\theta(\psi)$ and $K(\theta)$ relations are presented in figure 9.3. Soils (1) and (2) are hypothetical typical soils characterised by the $\theta(\psi)$ and $K(\psi)$ relations of Rijtema (1969), from which the $K(\theta)$ relations of figure 9.3 were derived. Default parameter values are provided with the PS123 software. $\theta(\psi)$ relations for soils (3) and (4) were determined in the laboratory, according to Topp & Zebchuck

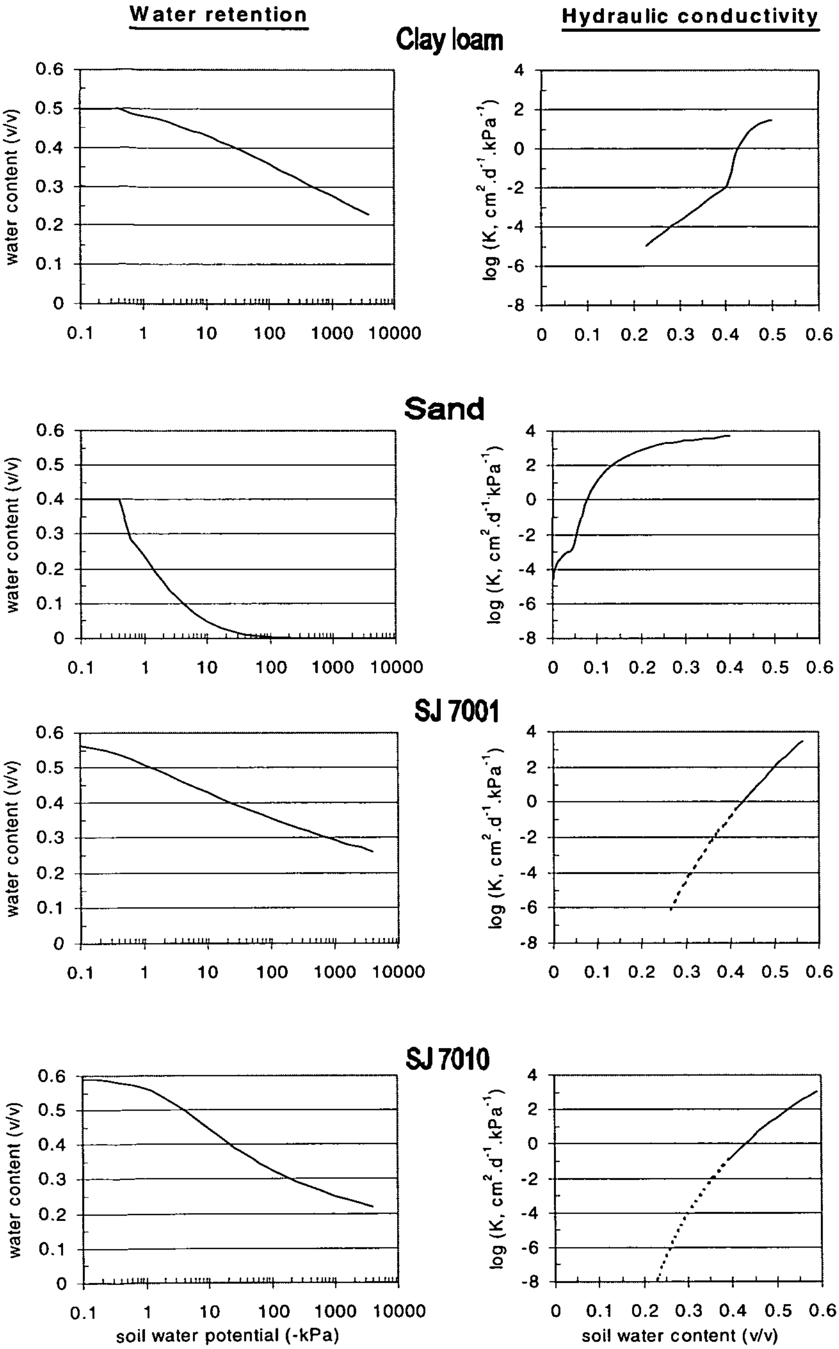


Figure 9.3 Water retention $\theta(\psi)$ and hydraulic conductivity $K(\theta)$ of the study soils

(1979). $K(\theta)$ relations for these soils were obtained through the instantaneous profile method according to Chong et al. (1981). Approximate functional relations were obtained by curve fitting through data observed on wet soils. The dashed lines in figure 9.3 represent extrapolations obtained with these equations.

In all exercises, the soil water content was not allowed to drop below θ_{pwp}, which was assumed to correspond with a soil water potential of −1600 kPa. The value of ψ_{leaf} was set to -1600 kPa in exercises with PS123. The maximum soil water content after excess drainage (θ_{fc}) was set to the water retained at -10 kPa for soils (1) and (2); and at the field measured values (2 days after saturation) of −2.8 kPa for soil (3) and −11.9 kPa for soil (4). In exercises 1 and 2, the initial soil water content was set to θ_{fc} for all rooted soil compartments. In exercises 3, 4 and 5, the soil water content of the surface layer, θ_1, after application of W cm water was simply calculated as:

$$\theta_1 = \mathrm{MIN}(\theta_{fc}, W/D_1) \qquad (9.12)$$

where D_1 is the depth of the lower boundary of the surface layer.

$D_1 = D_r$ (rooting depth) in exercises with WOFOST or PS123,. In exercises with SUCROS, which uses a multi-compartment soil representation, water in excess of θ_{fc} was passed on to underlying compartments:

$$\theta_j = \mathrm{MIN}(\theta_{fc}, W_{x,j-1}/(D_j - D_{j-1})) \qquad (9.13)$$

where

θ_j is water content of compartment j (compartment 1 is surface layer), (cm cm^{-1});

$W_{x,j-1}$ is water in excess of field capacity after wetting compartment j-1 (cm);

D_j is depth of lower boundary of compartment j (cm).

Note that WOFOST, SUCROS and PS123 use different descriptions of the distribution of water infiltrating in the surface soil. The simple set-up described above was merely meant to enable comparison of the different approaches to transpiration.

9.4 Results of the comparisons

Figure 9.4 presents the results of exercise 1, showing that the three models yield different results. PS123 calculates that transpiration takes place at the maximum rate during 10-30 days, followed by a sharp drop in water use. The reduction of the rate of transpiration calculated with WOFOST is a little more gradual and SUCROS predicts an even more gradual decrease. This implies that the bulk of total available soil water is consumed in a shorter time span in PS123 than in WOFOST and SUCROS. Cumulative transpiration is greater in SUCROS than in WOFOST and PS123, because SUCROS calculates water uptake from three soil compartments with a cumulative fixed depth of

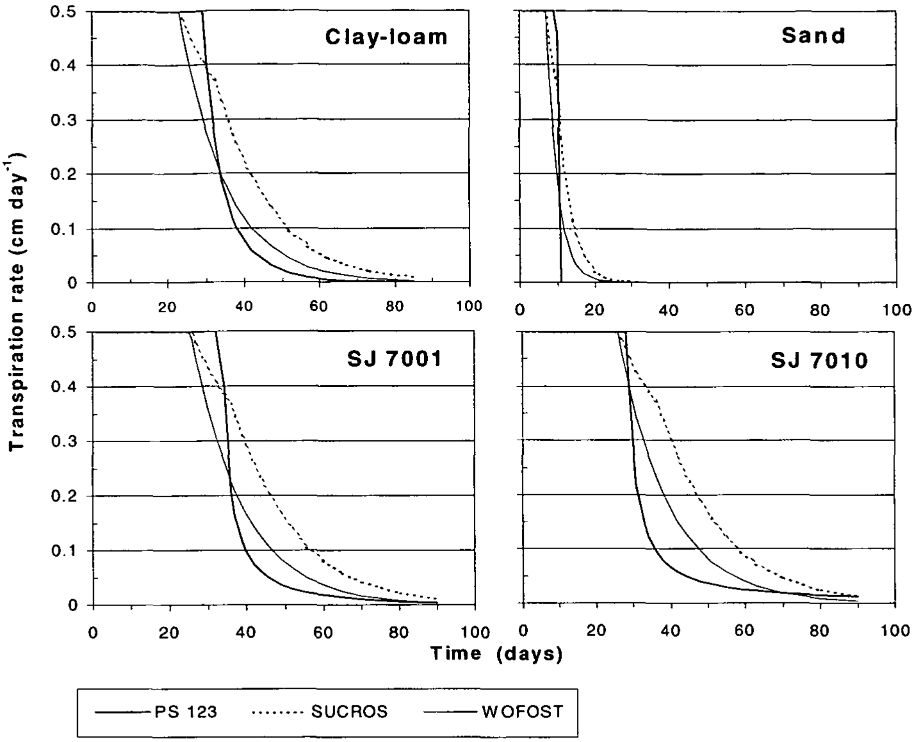


Figure 9.4 Calculated transpiration patterns after wetting soils to "field capacity". TR_m= 0.5 cm day^{-1}; Rooting depth = 100 cm

120 cm, even though the rooted soil depth is only 100 cm. The smaller cumulative transpiration on soil SJ7010 that was calculated with PS123 will be discussed later.

The results of exercise 2 (not shown), are identical for SUCROS and WOFOST: water is uniformly distributed and the rooted soil depth coincides with the lower boundary of the third soil compartment considered by SUCROS, at 120 cm depth.

The results of exercise 3, summarised in figure 9.5, show large differences between the models. WOFOST shows a rather slow but continuous response to the amount of water added. SUCROS has a peculiar oscillating response. This is clearly an artefact. The plateaux of the SUCROS curves (e.g. between 2 and 3.5 cm infiltrated water for soil SJ7001), reflect situations where water content in upper soil compartment(s) is not limiting (i.e. $\theta \geq \theta_c$), while there is no available water in deeper compartments. The dips in the curves (e.g. when some 4.5 cm of water have infiltrated in soil SJ7001) occur when the upper compartment(s) have reached field capacity and some water enters the underlying compartment. In this dip, increased water content results in an increased "effective root length" of the lower layer (equation 9.5), and consequently a decreased "maximum rate of water uptake per unit length of effective rooted depth" (equation 9.6).

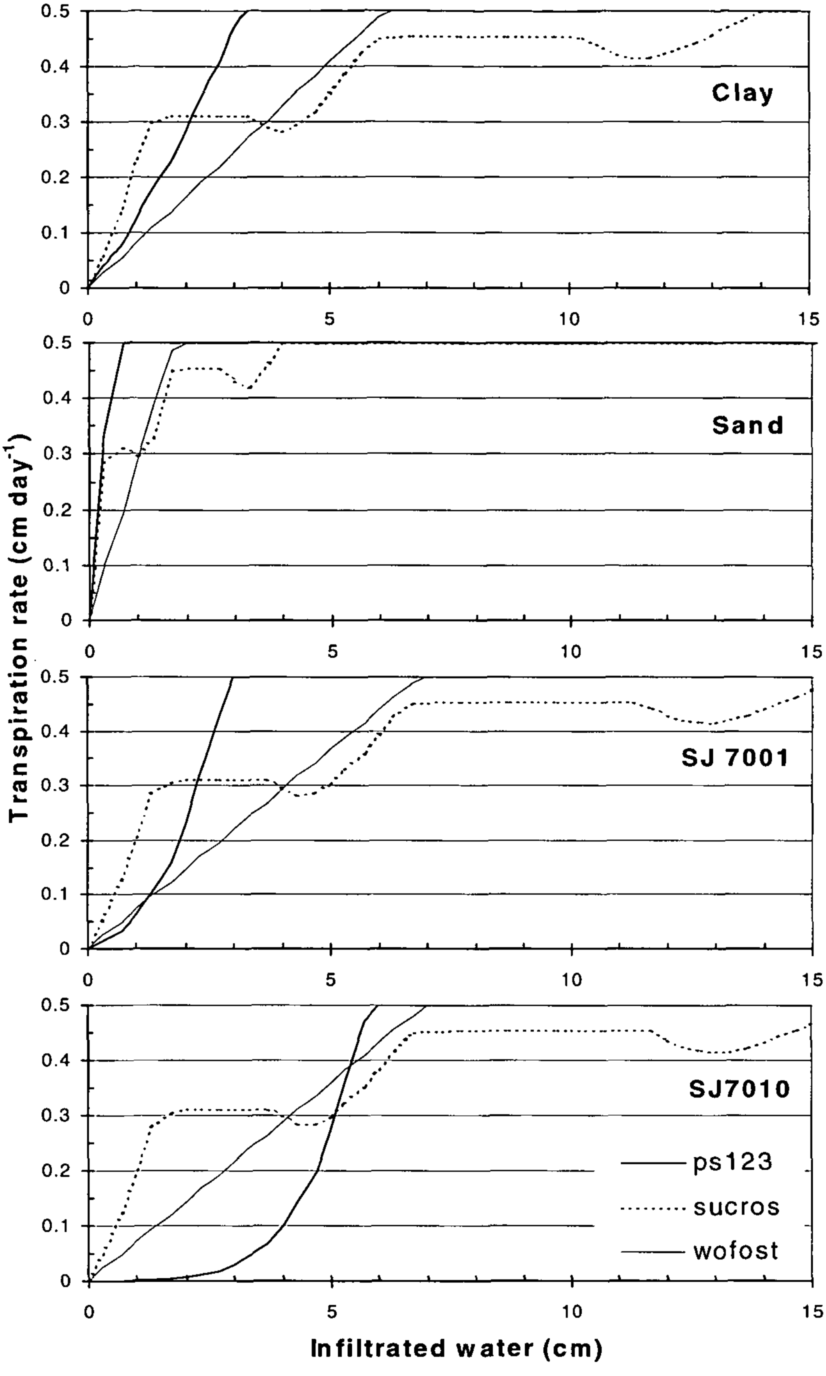


Figure 9.5 Actual transpiration rates calculated by three models, as function of water infiltrated on four dry soils. TR_m= 0.5 cm day^{-1}; Rooting depth = 100 cm

This is not sufficiently compensated by increased f_r in equation (9.7). One can easily verify that for crop group 5 and $TR_m = 0.5$ cm day^{-1} (see Appendix 1), c_r increases more rapidly with Θ_r (figure 9.2) than f_r (figure 9.1) in the range $0 < \Theta_r < 0.15$. Note that for PS123, water uptake from soil SJ7010 does not respond effectively until more than 2 cm water have infiltrated.

The results of exercise 4 are presented in figure 9.6. For a given amount of available water concentrated in the topsoil, all three models associate increased rooting depth with decreased transpiration. The PS123 model keeps $TR_a = TR_m$ over a wide range whereas SUCROS shows the most gradual decrease as a result of the multi-layered soil representation. For the sandy soil, PS123 predicts unconstrained transpiration for all rooting depths.

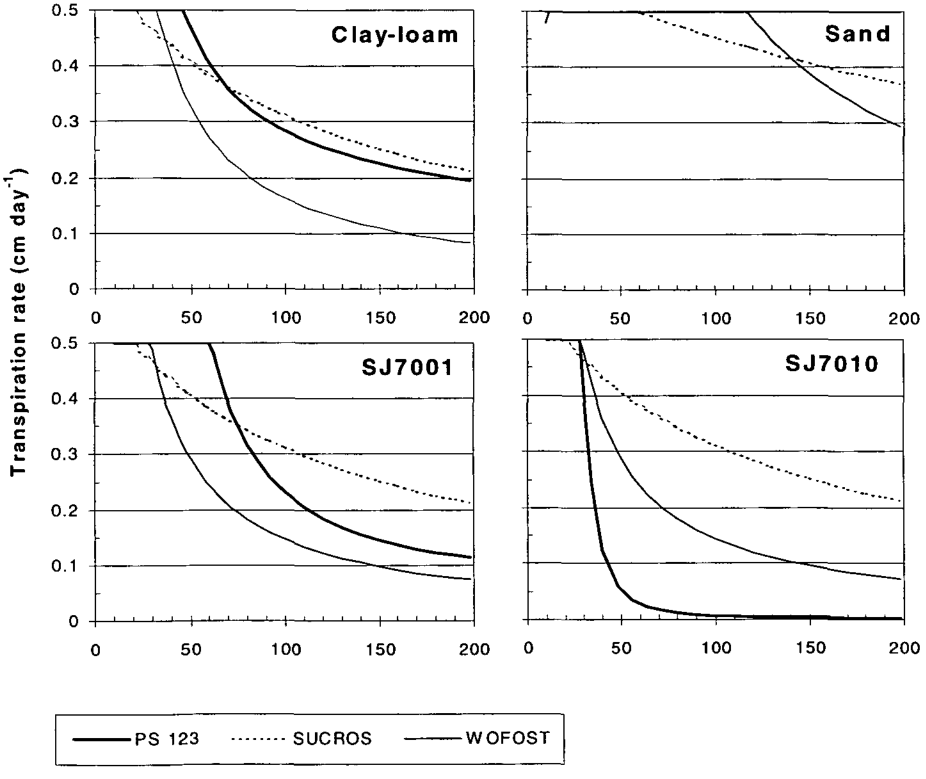


Figure 9.6 Transpiration rates calculated by 3 models, after application of 2.0 cm water on depleted soil, with varying rooting depth. TR_m= 0.5 cm day^{-1}.

The results of exercise 5 are presented in figure 9.7. As expected, differences between predictions of cumulative transpiration are less dramatic than between transpiration rates. However, the feedback mechanism mentioned in the introduction of

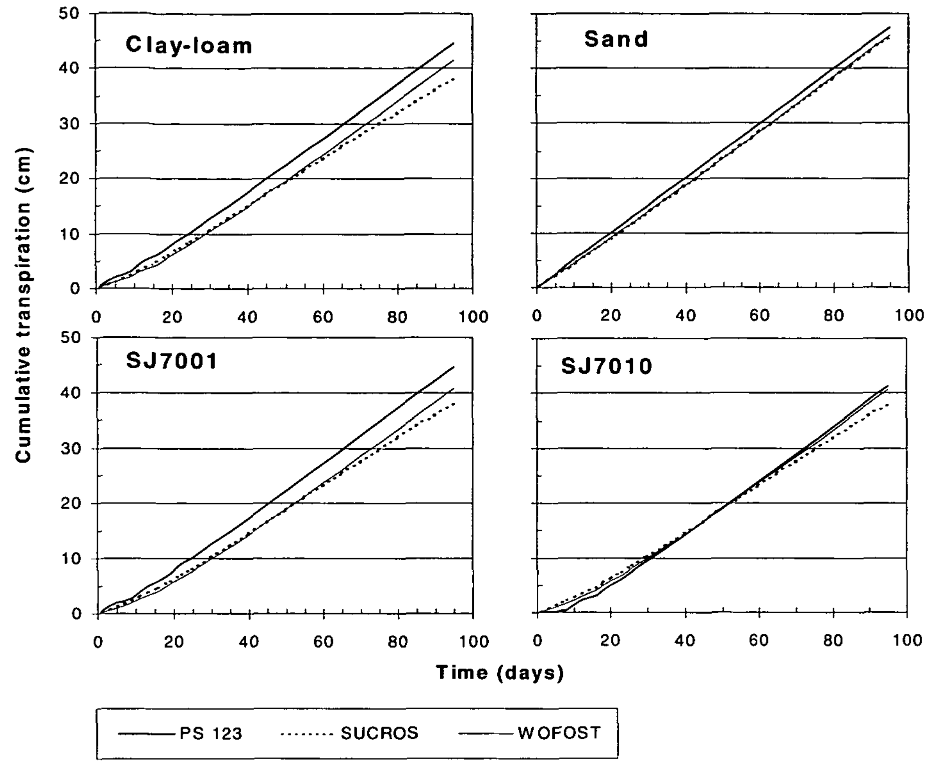


Figure 9.7 Cumulative transpiration with applications of 4 cm water, each 8th day, on initially dry soil. TR_m=0.5 cm day^{-1}; Rooting depth = 120 cm

this chapter is not sufficiently strong to cause convergence of the curves, because some water losses occur through the lower rooted soil boundary for WOFOST and SUCROS. Differences between PS123 and SUCROS run as high as 20 %. In this exercise, total water applied is the same as cumulative TR_m. If the drought periods are extended, the curves tend to converge. However, PS123 predicts periods without water stress succeeded by severe stress, whereas SUCROS predicts a more gradual pattern with a longer period of moderate stress.

9.5 Discussion

The results of the exercises show that different methods of calculating actual crop water uptake/transpiration, as used in crop growth models, may lead to considerably different results. These differences are partly explained by the need to curb data requirements and to simplify the descriptions of water storage, flow and uptake. Other causes of divergence are the way in which spatially variable data are treated (considered over the entire rooted soil or in soil compartments) and how approaches are adapted or combined.

WOFOST follows closely the approach of Doorenbos et al (1978). This approach is based on experience with irrigation trials: water applications, sufficiently large to wet the soil over the entire rooting depth, are alternated with dry spells. Their soil water depletion fractions (p) are intended to be used for such conditions and not for heterogeneous soil moisture profiles. This is illustrated by the small initial response to added water in exercise 3. In WOFOST, this water is distributed over the entire root zone, whereas in reality, it is concentrated in the surface layer, where it is readily available. Therefore, this approach seems, in its present form, not suited for application to dry land agriculture, where periods of more or less severe drought may be followed by varying supplies of rainwater, resulting in irregular distribution of water in the soil.

Artefacts in the results generated with SUCROS reflect the weak theoretical basis of this approach. The method to calculate f_r (figure 9.1), derived from Doorenbos et al (1978), seems incompatible with the concept of effective rooting (c_r, figure 9.2), adopted from Van Keulen & Seligman (1987). Results of the latter authors will not show any dips as in figure 9.5, because they assumed a different relation between f_r and Θ_r. This illustrates the risk of linking algorithms that were intended to be used for different conditions.

PS123's parameter value "13" in the estimation of R_{soil} (equation 9.11), is an average value for an "equivalent rooting depth". Results of Feddes and Rijtema (1972, figure 9.4) suggest that R_{soil} increases exponentially from the soil surface to the lower boundary of the rooted zone. This implies that water uptake is concentrated in the surface soil as long as water is readily available there. Gardner (1983) is of the same opinion. Driessen & Konijn (1992) deem it unlikely that plants would take up water that is strongly retained by a largely depleted surface soil when it is readily available in wetter, deeper parts of the rooted soil compartment(s). Hence their suggestion that representative ψ_{soil}, R_{root} and K-values can (only) be used for quantitative description of soil-plant-water systems if applied to an *"equivalent rooting depth"* that is defined as a function of the depth and distribution of roots over the (surface) soil. The question remains how this equivalent rooting depth should be determined.

The behaviour of soil SJ7010 in the exercises with PS123 provides interesting material for discussion of simplified theoretical approaches. Figure 9.8 shows R_{soil}, R_{plant} and U_{max} calculated according to equations (9.8), (9.10) and (9.11) for the soils with an assumed "equivalent rooting depth" of 100 cm. The curves for soil SJ7010 show that U_{max} drops sharply to almost nil near a soil water potential of –500 kPa, i.e. where the driving force (ψ_{soil}-ψ_{plant}) is still very great. This implies that the reason for the abrupt drop in U_{max} is the calculated value of R_{soil}, which is a function of K(θ) and $\theta(\psi)$ relations (figure 9.3). For example, at ψ_{soil} = –1000 kPa, calculated hydraulic conductivity (K) of the clay-loam is more than 200 times greater than that of soil SJ7010. The correctness of the K(θ) relations for soils SJ7001 and SJ7010 is questionable because values for the dry range were obtained by extrapolation from the wet range.

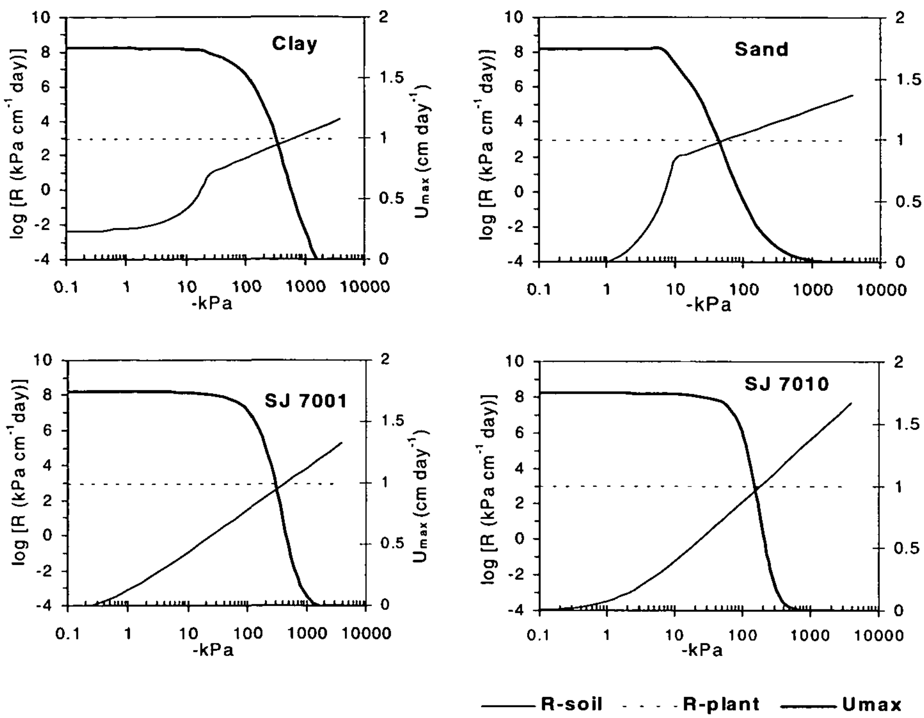


Figure 9.8 Water uptake relations for study soils as calculated by PS123, with rooting depth of 100 cm

Extrapolation of K(θ) relations is a common practice, because there are no operational methods to determine K at soil water potentials < -80 kPa. Very small hydraulic conductivity in the dry range is plausible for soil SJ7010, with its coffee powder structure, typical of Ferralsols. One could speculate that, even at relatively large water potentials, such soils have very few continuous water films around micro-aggregates to sustain water movement. The relations suggested in figure 9.8, however, seem to be exaggerated. One should also note the implications of the discontinuity of the K(θ) relation for water uptake from the clay-loam and sandy soils. Other popular descriptions of K(θ) (e.g. Van Genuchten, 1980) do not present such a discontinuity. Even at high potentials, determination errors of a factor 10 or more are quite common (Wösten et al., 1986, Leummens et al., 1995).

The foregoing illustrates how models based on physical theory have their merits, e.g. for educational purposes and for identifying research topics. It is equally clear that using such models for analytical purposes (e.g. biophysical assessment of land-use systems) may give disappointing results if they are not properly tested and/or surrogate input data are used. The differences between results of PS123 and the method of Doorenbos & Kassam (1979) used by WOFOST are illustrative for the danger of using semi-theoretical models that rely heavily on the use of default parameters (usually obtained by regression) with a very narrow experimental support. The method of

Doorenbos & Kassam (1979) is based on the electrical analogue model of Rijtema & Aboukhaled (1975), which only differs from the water uptake procedure in PS123 by using a different relation between R_{plant} and ψ_{soil}, also based on very few experimental data (see sections 8.2.3, 8.2.6 and 8.3.6).

9.6 Suggestions for an improved simple model

It is much easier to identify weak points in existing models than to develop attractive alternatives. The following is an attempt to address the main problems.

Keeping in mind that data needs must be within practical limits, the water depletion fraction approach could be adapted by differentiating water uptake over depth. Figure 9.9 illustrates this in a free interpretation of the results of Gardner (1983). As an example, five soil compartments are considered. It is assumed that *p(z)* relations can be derived from (experimentally determined or tabulated) *p* values for the soil as a whole, which is differentiated over the rooted soil as shown in figure 9.9. $f_r(\Theta_r,z)$ relations could be calculated with equation (9.4), substituting *p*(*z*) for *p*. If compartments are thin, one could set a maximum sink term (water uptake per unit soil volume) of, say, 0.02 $cm^3\,cm^{-3}\,day^{-1}$ (Hoogland et al., 1981). This method seems more appropriate than choosing a depth dependent maximum sink term (Hoogland et al., 1981; Prasad, 1988) because it fits in with the consistent results of more than 40 experiments with several

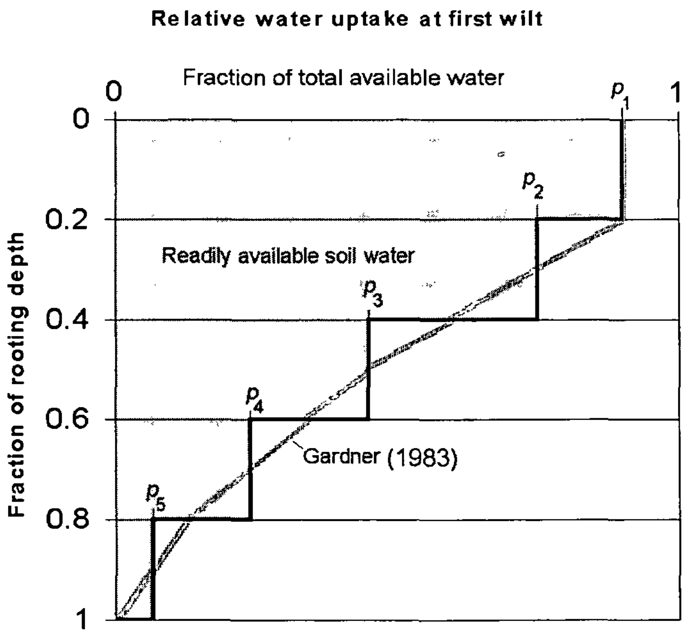


Figure 9.9 Schematic representation of depth dependent soil water depletion fractions

crops, reported by Gardner (1983); and because it leaves the possibility open to satisfy the evaporative demand of the atmosphere by extracting water from deeper zones, whenever it is readily available. An example of how this approach can be implemented in a computer programme is given in Appendix 2.

This approach seems reasonable for full crop canopies on deep, uniform, well drained soils. Uncertainties persist with respect to the determination of critical soil water contents and the occurrence of compensatory effects. These uncertainties can only be reduced by numerous (expensive) field studies. Their impact on model results can be assessed within the concept described above, by assuming different values of *p* and calculating TR_a/TR_m as either a function of (1) the water status of the compartment where it is most easily available or (2) the total amount of available soil water. Such uncertainty analyses can help to indicate limits of model accuracy, identify priorities for further research activities and field testing, leading to less uncertainty and improved model accuracy.

9.7 Conclusions

1. Different methods to calculate actual transpiration, as used in crop growth models, may result in considerably different calculated daily and cumulative values.

2. Models that perform calculations on the rooted soil as a whole seem inappropriate for dynamic modelling of water uptake in soils that are subject to irregular cycles of drying and wetting with varying amounts of water. It is necessary to consider several compartments within the root zone, each with its specific soil water uptake relations.

3. Using surrogate input data (e.g. roughly estimated or extrapolated $K(\theta)$ relations) in refined water uptake models may well give worse results than simple models with modest data input requirements.

10. ASSIMILATE PARTITIONING IN PLANTS AS CONDITIONED BY EXTERNAL CONDITIONS AND PHENOLOGY: PRIORITY RULES FOR SUMMARY CROP GROWTH MODELS

10.1 Introduction

Crop growth models are becoming increasingly important tools in land use systems analysis even though their value for these purposes has been seriously questioned (e.g. Passioura, 1996; Mutsaers & Wang, 1999). Important points of concern include the lack of balance between modelled carbohydrate sources and sinks (Monteith, 1996) and the neglect of feedback and feedforward mechanisms (Van Diepen et al., 1998; Mutsaers & Wang, 1999; Connor & Fereres, 1999).

The objective of this chapter is to present a summary modelling approach that takes these aspects into consideration. The rationale is based on the concept that plants are capable of adapting themselves - within limits - to changing environments. The chapter focuses on the optimisation of assimilate allocation to crop organs, as a function of phenological development and external conditions, notably light, temperature and water availability. Effects of nutrients and disturbances by toxic elements or diseases are not addressed.

The chapter is structured as follows. Section 10.2 discusses assimilate partitioning and current modelling approaches. Section 10.3 presents plants as "smart systems". The rationale behind the proposed summary model is presented in section 10.4 and section 10.5 describes how this was implemented. Section 10.6 shows preliminary results of growth monitoring experiments and model outcomes with soybean and sugarcane in the study regions. Strengths and weaknesses of the approach are discussed in section 10.7. The conclusions are presented in section 10.8.

10.2 Assimilate partitioning: concepts and modelling approaches

Assimilate partitioning is often defined as the distribution of newly synthesised biomass among crop organs (Wilkerson et al., 1983; Supit et al., 1994; Stroosnijder & Kiepe, 1998). The partitioning fraction FR_{org} to organ *org* (e.g. leaf, stem, root, reproductive organs) is then usually assessed by:

$$FR_{org} = (dS_{org}/dt)/(dS_{crop}/dt) \qquad (10.1)$$

where,

S_{org} is total (living + dead) dry mass of organ *org* (leaves, stems, roots etc..) per unit land surface area (e.g. kg ha^{-1});

S_{crop} is total (living + dead) dry mass of the crop (leaves + stems + roots etc..) per unit land surface area (kg ha^{-1});

EC includes growth respiration, energy expenses for ion uptake and losses incurred in the formation of secondary reaction products, which depend primarily on biomass composition and nutrient sources (Penning de Vries et al., 1989).

The dynamics of S_{org} and S_{crop} and their derivatives over time can be assessed by monitoring crop growth. Equation 10.1 can then be used to describe the variations in FR_{org}'s over the growing season, usually not as a function of time, but as a function of the phenological development stage (DVS) of the crop.

Crop growth modellers use these values of FR_{org} as input to their models to describe new situations, calculating dS_{org}/dt (or more commonly $\Delta S_{org}/\Delta t$) by equation 10.3, which combines the inverse of equation 10.1 with equation 10.2:

$$dS_{crop}/dt = (P\text{-}MRR)*EC \qquad (10.2)$$

$$dS_{org}/dt = FR_{org}*(P\text{-}MRR)*EC \qquad (10.3)$$

where,

P is photosynthesis rate per unit land surface area (kg CH_2O ha^{-1} day^{-1});

MRR is maintenance respiration rate per unit land surface area (kg CH_2O ha^{-1} day^{-1})

EC is efficiency of conversion of primary assimilates (sugars) to structural plant material (kg CH_2O kg^{-1} biomass).

It is obvious that accurate descriptions of crop growth and yield predictions depend heavily on a correct assessment of the FR_{org}'s, and not just of those that refer to harvestable parts. Estimation of leaf growth is particularly important, because P is co-determined by S_{leaf}. Furthermore, underestimation of one factor implies overestimation of another.

The procedure described above seems to be straightforward, but the method to derive FR_{org}'s and the use of equation 10.3 in crop models present several flaws:

1. Possible losses in dry mass are not properly accounted for by monitoring crop growth: (a) when respiration losses occur in excess of assimilation; (b) when assimilates are reallocated from one organ to another; and (c) when dead plant material decays, e.g. by fungi;

2. equation 10.3 suggests that dry matter is formed from primary assimilates before it is distributed over the plant, which is obviously incorrect;

3. subtraction of MRR from P implies that maintenance always has absolute priority over growth, which is untrue. Fully expanded leaves are usually incapable of using imported assimilates (Dickson & Isebrands, 1991; Marschner, 1995). These leaves die if they cannot maintain a favourable carbon balance, e.g. due to shading, even when the carbon balance is favourable for the plant as a whole. Another example are the assimilate reserves left in recently cut ratoon sugarcane.

Their remobilization is used for the growth of a new plant canopy, rather than to maintain the entire old root system (Alexander, 1973; Ball-Coelho et al., 1992). Compare also p. 54 and 55 of Penning de Vries et al. (1989).

These problems are mitigated in the approach of Driessen & Konijn (1992), in their PS123 model. They work with gross assimilate partitioning fractions, $FR_{g,org}$, and calculate the growth rate of organ *org* as:

$$dS_{org}/dt = (FR_{g,org} * P - MRR_{org}) * EC_{org} \quad (10.4)$$

hence,

$$FR_{g,org} = [(dS_{org}/dt)/ EC_{org} + MRR_{org}]/P \quad (10.5)$$

where, MRR_{org} is the maintenance respiration rate of *org* ($kg\,ha^{-1}d^{-1}$) and EC_{org} the conversion efficiency of primary assimilates to structural material of *org* ($kg\,CH_2O\,kg^{-1}$ biomass).

Another problem related to the approach described is that the FR_{org}'s are assumed to be crop specific functions, depending predominantly (or exclusively) on DVS. Figure 10.1 shows "reference" partitioning fractions over the growing season for soybean crops suggested by Penning de Vries et al. (1989), Jones et al. (1989) and Boon-Prins et al. (1993) alongside values that were obtained after adjustments (called model calibration) by Boon-Prins et al. (1993) and Gerdes et al. (1993). The differences are considerable. Some curves suggest a continuous decrease of partitioning to leaves, whereas others suggest an increase during a certain period. Partitioning to stems during vegetative development may either show continuous increase or decrease or a more irregular pattern. One could conclude from these discrepancies that, apart from some trivial trends, differences between soybean crops are so great that the term "reference values" is misplaced. These differences may partly be ascribed to genetic differences among cultivars, but environmental factors may be equally or more important. Hence, describing assimilate partitioning solely as a function of phenological development may be satisfactory when growth conditions are similar to those under which the crop monitoring experiments were conducted that were used to determine the allocation fractions, i.e. at a similar site, with similar weather and a similar planting date. Problems are expected when growth conditions are different.

Handbooks on plant physiology (e.g. Wilkins, 1984) contain numerous examples of the influence of environmental factors on growth differentiation. The basic processes are only partly understood and involve complex bio-physico-chemical reactions at cellular and sub-cellular levels (Cosgrove, 1986, Kasperbauer, 1988; Marschner, 1995) which cannot be implemented in crop growth models for practical application in regional studies. Macroscopically, growth differentiation seems to strive for the establishment of a functional equilibrium between plant components (Brouwer, 1963, 1983; Smith et al., 1999). Sharpe & Rykiel (1991), based on the work of Bloom et al. (1985) suggested the term "optimum resource allocation hypothesis". Examples of adaptive responses are:

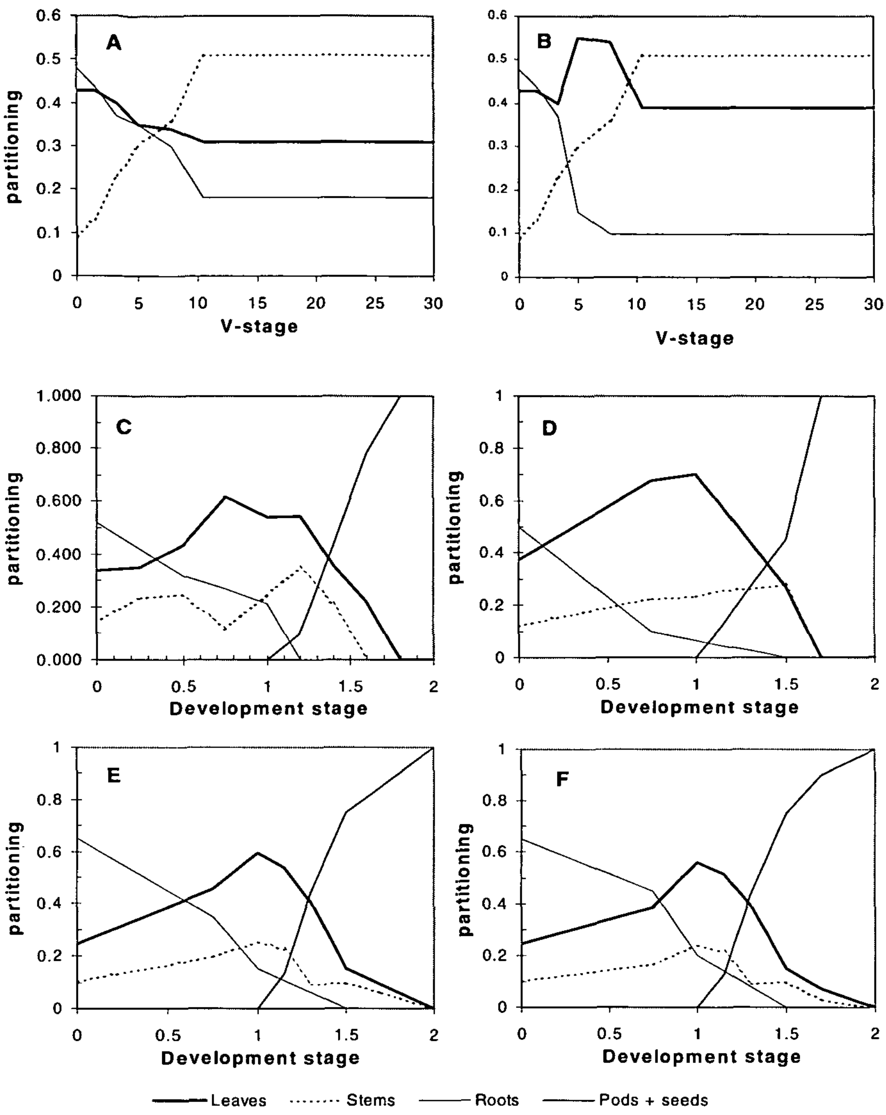


Figure 10.1 Biomass partitioning functions for soybeans. (A) Reference values given by Jones et al. (1989); (B) after calibration for c.v. Kingsoy by Gerdes et al. (1993); (C) reference values derived from Penning de Vries et al., (1989, tables 11 and 18); (D) Initial values WOFOST (Boon-Prins et al., 1993); (E) and (F) Region specific values WOFOST, after calibration for 2 sets of crop types (Boons-Prins et al., 1993)

- crops that experience gentle to moderate drought stress tend to form deeper root systems than crops with ample water supply. The first are more resistant to drought in later stages of development (e.g. Dwyer & Stewart, 1985; Tilman, 1988);

- accidental leaf loss (e.g. by grazing or insect damage) furthers allocation of assimilates to the leaves (Brouwer, 1963; Bovi, 1983; Smit, 1989; Simons & Johnston, 1999);
- low levels of radiation (e.g. induced by shading or canopy competition) in warm and moist conditions promote expansive stem growth (Kasperbauer & Hunt, 1989; Ephrath et al., 1993; Behairy, 1994; Kang et al., 1998).
- many plants have adaptive mechanisms to cope with water logging; for example, adaptation to flooding of soybeans involves preferential allocation of photosynthates to the development of adventitious roots and aerenchyma formation (Santos et al 1989; Bacanamwo & Purcell, 1999). In some soybean cultivars, stress is only conspicuous during adaptation from aerated to waterlogged conditions and *vice versa* (Mozafar et al., 1992).
- Most plants, if not all, can temporarily store assimilates in the form of starch or sugars, which can be remobilized in a later stage and translocated for structural growth. Such reserves can contribute substantially to seed yield (Gallagher et al., 1976; Bidinger et al., 1977), but they can also be used for rapid recovery of the leaf canopy after a period of stress or disturbance during vegetative growth (Glasziou et al., 1965; Alexander, 1973; Barnett & Pearce, 1983; Chapin et al., 1990).
- cold and/or drought during the vegetative stage enhance allocation of assimilates to the carbohydrate reserve storage pool and curb the expansive growth of above ground vegetative organs (Van Dillewijn, 1952; Alexander, 1973, Jones, 1985; Chapin et al., 1990; Werker et al., 1999);
- mild water shortage during the reproductive stage enhances the allocation of assimilates to seeds and/or increases the rate of seed ripening (Costa & Marchezan, 1982; Grashoff & Verkerke, 1991; Gutiérrez-Boem & Thomas, 1999).

Interesting alternative approaches to describe partitioning in response to changing conditions, were suggested by Schulze et al. (1983), Huck & Hillel (1983) and Connor & Fereres (1999). Their models use optimisation algorithms to maximise shoot growth, as restricted by the water uptake capacity of roots. Their results for young plants show a fair correspondence with observed data. However, these models are not suited for practical application to land use systems because they require detailed information on the relation between water uptake and root length or mass and/or on the hydraulic properties of soil and plant (see sections 8.2.2 and 8.2.3 of this thesis). Furthermore, the optimisation procedures used consider immediate needs only and ignore the possibility of storage in reusable carbohydrate reserves and reproductive organs.

10.3 Plants as "smart systems"

Observed plant responses as mentioned in the previous section suggest that, in analogy with economics, plants only "invest" assimilates in organs if they "expect" a satisfactory return. Such returns can be obtained on the short, medium or long term. In the context of plant growth we define these as:

- Short term: within one or a few days;
- medium term: at a later stage within the growing cycle;
- long term: for future generations

Investment in leaf growth generally implies greater light interception, resulting in increased photosynthesis on the short term. Investment in stems means that leaves can be spaced further apart, e.g. to avoid mutual shading, or that plants become taller in relation to their competing neighbours at the short or medium term. Investment in roots means better anchorage (at the short to medium term), improved conditions for water uptake (short term) and more available water during possible dry spells in the future (medium term). Investments in carbohydrate reserves form a medium term protection against the risk of extreme stress or partial destruction (e.g. grazing). Investment in seed is a pre-condition to establish a next generation (long term). This reasoning views plants as "smart systems". Note that the terminology used above is quite common in plant physiology, population biology and ecology (Parker, 1968; Bloom et al., 1985; Bloom, 1986; Tilman, 1988; Chapin et al., 1990, Simons & Johnston, 1999), but rarely encountered in crop growth modelling.

The "smartness" of plants certainly has its limitations:

1. Contrary to some popular belief, it has never been proven that plants have foresight. Medium- and long term investments are more likely to be based on genetic blueprint and past "experience".
2. The scopes for adaptations differ between species and varieties. Most species don't have the flexibility of *Eleocharis vivipara*, an amphibious sedge, that develops C_4-like characteristics under terrestrial conditions and C_3-like traits under submerged conditions (Ueno, 1998). Succulents are genetically prepared to invest in drought resistance but in humid environments they would not be able to adapt to the extent that they can compete with plants with thin broad leaves.

An interesting implication of (1) and (2) is that it is possible to "fool" plants (e.g. forcing flowering by artificial light) and to breed crops that are adapted to artificial environments. For example, high yielding short straw varieties of rice are well adapted to artificial environments with controlled water levels and monocropping, but not to natural environments with fluctuating water levels and tall neighbours competing for light.

10.4 Rationale of the "smart crop" model

The summary model presented here is based on the idea that crops optimise assimilate allocation within genetically defined limits, rather than either following rigid DVS-dependent functions or solely covering immediate needs. This concept shifts the focus from *describing how plants act* to *what would be in the best interest of the plant.* Obviously, this can only contribute to improved crop growth modelling if one can quantify the costs and returns of assimilate investments. For the time being, this is very restricted. Hence pragmatic assumptions were made and simple decision-tree-like priority rules were established rather than complex iterative optimisation algorithms.

10.4.1 Roots

The cost of the root system is determined by the summed carbohydrate requirements for growth and maintenance. However, maintenance respiration of a root system is very difficult to assess (Lambers et al., 1983, Goudriaan, personal communication, 1999). Furthermore, data published so far are insufficient for a simple yet accurate quantification of returns on investments in root growth such as improved anchorage and increased water uptake. As a first approach, partitioning to the roots is postulated to be proportional to the difference between the root mass (S_{root}, $kg\,ha^{-1}$) and a target value, $S_{root,max}$. In the case of water stress, partitioning to roots may become greater, when assimilates that are not used for shoot growth become available. Root growth ceases when the root mass exceeds $S_{root,max}$, and resumes again once death or respiration losses have caused a decrease of S_{root} to below $S_{root,max}$. This simple representation is based on the notion that the ratio between root and shoot growth increases when water availability is restricted (Brouwer, 1983, Pugnaire et al., 1999). However, in absolute terms, root growth does not usually increase because the total assimilation rate decreases (see e.g. Spollen et al., 1993).

10.4.2 Leaves

Knowledge of "cost/benefit" aspects of leaf growth is greater than for roots. Both costs and benefits can fairly well be quantified. Costs are incurred in the conversion of assimilates to leaf material and in leaf maintenance; benefits are derived from increased photosynthesis as a result of increased light interception. Disregarding the so-called opportunity costs (see Chapin et al., 1990), leaf growth would be promoted if $dP/dS_{leaf} > dMR_{leaf}/dS_{leaf}$. Figure 10.2 schematically shows costs and benefits, calculated according to Driessen (1997) as a function of S_{leaf} and leaf area index (LAI, $m^2\,m^{-2}$) for a hypothetical C_3 crop with constant specific leaf area and different levels of temperature, radiation and water availability. It illustrates that the return on investment in leaves decreases when leaf mass (and hence LAI) increases and marginal benefits from investments in leaves become progressively smaller, whereas marginal costs increase in proportion to leaf mass. The break even point, indicated by the dashed vertical lines in figure 10.2, shifts to smaller leaf mass values (1) when assimilation is restricted due to stomatal closure as a result of water stress; and (2) when photosynthesis decreases due to low levels of incoming light (e.g. heavily overcast sky), notably at high temperature.

In the present approach it is assumed that the crop produces leaf material only when marginal benefits outweigh marginal costs (see Bloom et al., 1985).

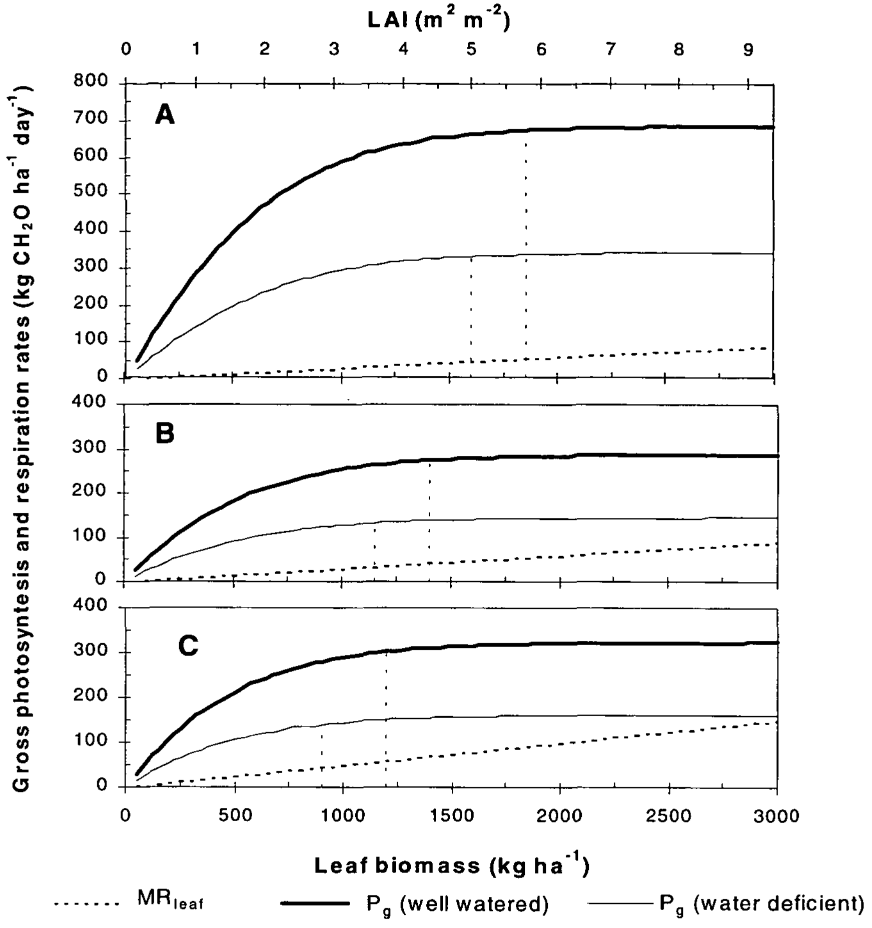


Figure 10.2 Schematic representation of gross photosynthesis (P_g, kg CH_2O $ha^{-1}day^{-1}$) and leaf maintenance respiration (MR_{leaf}, kg CH_2O $ha^{-1}day^{-1}$) rates as functions of leaf biomass (S_{leaf}) and leaf area index (LAI). A: high irradiance, high temperature; B: low irradiance, low temperature; C: low irradiance high temperature. Calculated according to Driessen (1997). The dashed vertical lines indicate where $dP_g/dS_{leaf} = dMR_{leaf}/dS_{leaf}$

10.4.3 Stems

Cost/benefit relations for stems cannot be established in simple crop growth models which keep track of stem and leaf biomass per unit area, but disregard crop height and the spacing between individual plants and rows. The approach suggested, for uniform crop stands, assumes that for each unit of leaf growth a genetically defined minimum fraction of available assimilates is allocated to stems. Investment in stem growth exceeds this minimum when investment in leaves gives no net return (e.g. when LAI is large; see previous section) except when the crop is subject to water stress, because this would expose the canopy even more to the drying atmosphere.

10.4.4 Reproductive organs

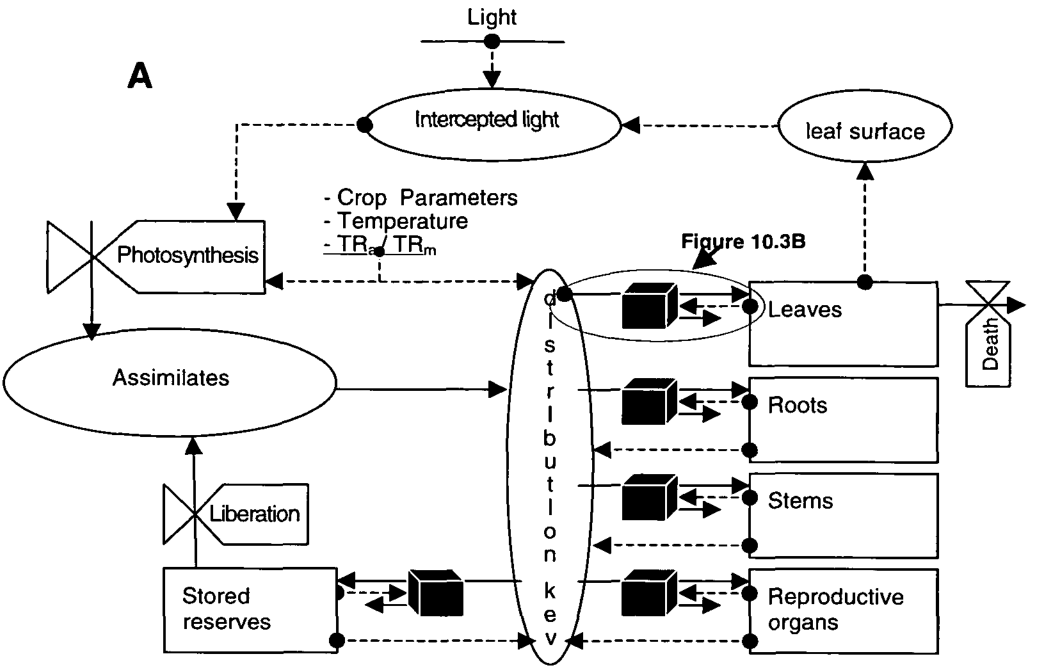
Investment in reproductive organs only starts after a period of vegetative growth, providing to the plant the means for seed production. In the approach suggested here, like in most crop growth models, the transition from vegetative to reproductive growth occurs at a characteristic DVS, determined by genetic blueprint and described by a function of temperature and/or photoperiod over time. After anthesis, the fraction of assimilates partitioned to reproductive organs (FR_{genr}) increases from practically nil to 1. It is assumed that during this transitional stage the minimum value of FR_{genr} increases linearly with the relative development stage (RDS) but more assimilates may be allocated to reproductive organs if assimilate demand of vegetative organs is depressed, e.g. by mild drought stress. The transitional period is short for determinate varieties and longer for indeterminate ones.

10.4.5 Assimilate reserves

The summary model presented here considers only assimilate reserves in stems and germinating seed. Smart plants would have a dilemma between satisfying short-term needs and setting aside assimilate reserves to protect themselves against risks at medium and long term. Since the immediate future is less uncertain than long term prospects, plants might prefer to let short-term returns prevail over investments that fence off possible risks at later stages. In a competitive environment, the price to pay for medium/long term investment would be high when short term needs (e.g. leaf area) are not satisfied. Neighbours would claim the available space and the growth conditions of the plant would deteriorate. Therefore, it is assumed that substantial medium and long-term investments in excess of a genetically determined minimum (which might be nil) occur only when investments with a short-term return are no alternative. This may happen under stress conditions (e.g. low temperature, water insufficiency), and in a closed crop canopy before seed filling. Obviously, the crop must be physically adapted to store reserves. In sugarcane, stem growth would not just improve light interception, but also present a medium term investment in storage space for sugar. Stored reserves are remobilized when conditions are favourable for structural growth or when new structural sinks (e.g. reproductive organs) appear.

10.5 Implementation

The approach suggested above was implemented in the summary crop growth model PS123 (Driessen, 1997). A comprehensive explanation of that model is given by Driessen & Konijn (1992). A brief outline of the adapted model is given in figure 10.3. The methods used to describe essential processes are indicated in table 10.1. Calculations are done for successive time intervals (Δt) of 1 day. The original PS123 code was translated from BASIC to FORTRAN 77. Substantial modifications, discussed below, consider (1) the phenological development stage concept, (2) the calculation of water uptake/transpiration, and (3) the introduction of "smart crop" concepts.



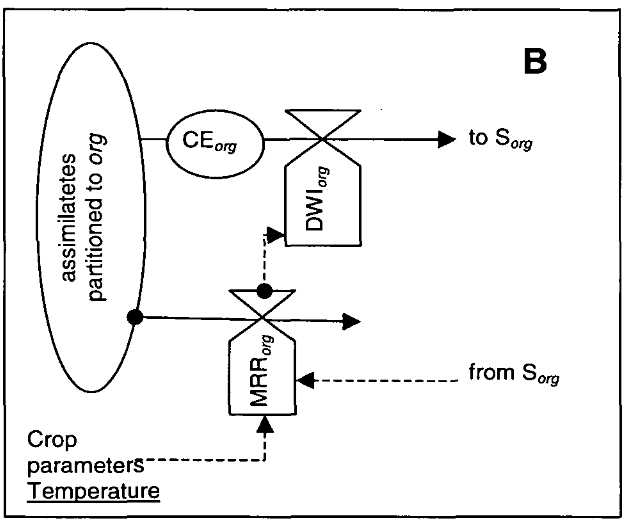


Figure 10.3 Relational diagram of adapted crop growth simulation model. A. General outlines; B. submodel for assimilate partitioning and dry matter increase, indicated by black boxes in A. *org*: crop organ (leaf, root, stem, stored reserves, reproductive organs); CE: conversion efficiency; S: dry mass; MRR maintenance respiration; DWI: Dry matter increase

Table 10.1 Principal features of the crop growth model.

Crop growth

Feature	Description
Gross photosynthesis rate	Driessen & Konijn (1992, p. 120-123); function of intercepted radiation and light use efficiency; levels off at temperature dependent light saturation plateau.
Gross assimilate partitioning among crop organs	Depends on priority for growth of different organs and availability of sinks. A storage pool in the stem acts as assimilate source and sink. Details see text.
Maintenance respiration rate	Driessen (1996); proportion of mass for each organ, depends on temperature (Q10=2); maintenance respiration is discounted from assimilates partitioned to each organ. This may result in negative growth.
Conversion efficiency of primary assimilates to plant material	Organ specific parameters, based on biomass composition. Conversion after partitioning and subtraction of maintenance requirements. Details see text.
Leaf mass and area dynamics	Driessen & Konijn (1992, p. 123, 129). Source limited. Specific leaf area (leaf area per unit leaf mass) varies between minimum and maximum values as a function of development stage; but single average values were used for this study. Leaves die due to physiologic ageing. Eldest leaves die first. Additionally, leaf area may decrease due to large respiration rate, e.g. in case of drought stress or excessive mutual shading.
Links between crop growth and water balance	Adapted from Driessen (1996). - Gross photosynthesis rate is assumed to be linearly related to TR_a/TR_m; - Assimilate partitioning is affected (see text); - Canopy temperature rises. A linear relation is assumed between (TR_m-TR_a) and maximum temperature increase of the crop canopy. This affects phenological development rate, leaf ageing and maintenance respiration rates.

Water balance

Feature	Description
Rooted depth	As PS123. Rooted zone extends at constant rate until crop or soil limited maximum depth is reached.
Potential evapotranspiration rate (E_0)	As PS123: according to Penman (1948)
Maximum transpiration rate (T_m)	Function of E_0, leaf area index (LAI), light extinction coefficient for global light k_e and a wind turbulence factor F (Driessen & Konijn 1992, p. 152): $TR_m = E_0 * (1 - e\text{-}k_e.LAI) * F$
Reduction of transpiration rate due to water stress	According to method proposed in chapter 9 and described in appendix 2.
Reduction of transpiration rate due to oxygen stress	Adapted from Driessen & Konijn (1992). See appendix 2. Function of soil air content and crop tolerance. Transpiration is not limited when air content $\geq$ 0.08 $cm^3\,cm^{-3}$.
Maximum evaporation rate (E_m) from wet cropped soil surface	Function of E_0, LAI (including dead leaves) and extinction coefficient for global radiation ($k_{g,e}$): $E_m = E_0 * e\text{-}k_{g,e}.LAI$
Actual evaporation rate (E_a)	*Supit et al. (1994), as function of number of days after last rain>E_0.* Extraction from top layer only.
Infiltration	Gauged rainfall + irrigation; not corrected for interception by leaves or runoff losses.
Percolation and deep drainage.	Simple "tipping bucket" approach, using field capacity concept (see appendix 2).

10.5.1 Algorithm for determining the development stage

The relative development stage (RDS) indicates the degree to which a crop has completed morphological development. In the PS123 model (Driessen, 1997), RDS increases, from 0. at emergence to 1. at maturity, according to the thermal time concept. The adapted model presented here is a pragmatic approach to approximate published photoperiod/temperature conditions for vegetative and reproductive development of the sugarcane and soybean crops analysed in this study. It recognises 3 phases:

1. a juvenile phase ($0<RDS<1$) during which the crop is not sensitive to environmental incentives for reproductive development;
2. an adolescent/adult phase ($1\leq RDS<2$) starting when plants become receptive to inductions for reproductive development and ending at anthesis or during seed formation, in dependence of plant genetics;
3. a reproductive/maturation phase ($2\leq RDS\leq 3$), characterised by seed formation and maturation.

The rate of phenologic development (DVR, d^{-1}) is calculated as:

$$DVR = DVR_{max}(I)*C(I) \tag{10.6}$$

where,

I is the phase of development (1 = juvenile; 2 = adolescent/adult; 3 = reproductive/ maturation),

$DVR_{max}(I)$ is the maximum development rate (at optimal photoperiod/temperature conditions) in development phase I (d^{-1});

C(I) is a correction factor ($0\leq C(I)\leq 1$) for photoperiod and/or temperature (average, minimum, maximum, day or night);

RDS is adjusted at the end of each time interval Δt (d) according to:

$$RDS=RDS + \Delta t*DVR \tag{10.7}$$

Examples of the calculation of the correction factors C(I) for soybean and sugarcane are given in section 10.6.1.

10.5.2 Assimilate partitioning and growth

The algorithm used to calculate the partitioning of assimilates between sinks and the dynamics of dry matter production is explained below, in 9 steps. Acronyms used in the computer programme were adapted (e.g. with subscripts) to improve readability.

Step 1. The rate at which assimilates become available for growth (AA, kg CH_2O $ha^{-1}d^{-1}$) is calculated as:

$$AA = FGASS + AAL \tag{10.8}$$

where

FGASS (kg CH_2O $ha^{-1}d^{-1}$) is the potential gross photosynthesis rate, calculated according to the PS123 model.

AAL (kg CH_2O $ha^{-1}d^{-1}$) is the rate at which carbohydrates from the labile pool of starch or sugar reserves in the stem can be remobilized:

$$AAL = EC_{lib} * FRLIB * MIN(FRAAMXE * S_{labst}, EASYLAB) \qquad (10.9)$$

where,

EC_{lib} is the efficiency of conversion and remobilization of stored reserves to CH_2O equivalents in the phloem stream (kg kg^{-1});

FRAAMXE is the maximum rate of carbohydrate remobilization in relation to the total amount of stored reserves (kg kg^{-1} day^{-1});

EASYLAB is the maximum rate of carbohydrate remobilization per unit cropped surface area (kg CH_2O ha^{-1} day^{-1});

S_{labst} is the total amount of stored carbohydrate reserves (kg ha^{-1});

FRLIB is a tentative expression that describes the remobilization rate of carbohydrates from the storage pool in relation to average temperature (T_{24h}) and water sufficiency:

$$FRLIB = f(T_{24h}) * TR_a / TR_m \qquad (10.10)$$

$f(T_{24h})$ is a simple linear expression yielding values between 0. and 1 (see section 10.6.1: Estimation of model parameters, and figure 10.8).

Step 2. The fraction of AA allocated to reproductive organs ($FR_{g,genr}$) is nil during vegetative growth. After anthesis, the basic value of $FR_{g,genr}$ is assumed to increase linearly with RDS until it reaches a plateau level of 1.0.

Step 3. The fraction of AA that is earmarked for roots, ($FR_{g,root}$) is initialised by the user defined parameter $FR_{g,root,max}$ and is assumed to be proportional to the difference between actual root biomass (S_{root}, kg ha^{-1}) and a user-defined "target value" ($S_{root,max}$, kg ha^{-1}). $FR_{g,root}$ cannot exceed the fraction of AA that is left over after deduction of assimilates required for reproductive organs:

$$FR_{g,root} = MIN(1.-FR_{genr},\ FR_{g,root,max} * (S_{root,max} - S_{root}) / S_{root,max}) \qquad (10.11)$$

Step 4. To calculate the fraction of AA that is partitioned to leaves ($FR_{g,leaf}$) it is first checked if increased leaf mass (resulting in increased LAI), would enhance crop performance (see figure 10.2):

$$\text{If } (dFG50 \leq dMRR50) \text{ then } FR_{g,leaf} = 0. \text{ else}$$
$$FR_{g,leaf} = (1.0 - FR_{g,root} - FR_{g,genr}) / (MINSL+1.) \qquad (10.12)$$

where dFG50 is the increase in gross photosynthesis rate (kg CH_2O ha^{-1} day^{-1}) of the crop if 50 kg ha^{-1} more leaves were present; and dMRR50 is the increase in maintenance respiration rate (same units as dFG50) with 50 kg ha^{-1} more leaves. MINSL is explained in step 5.

Step 5. Basic partitioning to stems ($FR_{g,stem}$) is proportional to the partitioning to leaves. i.e. it is assumed that for each unit of assimilates allocated to leaves, at least MINSL units must be allocated to stems:

$$FR_{g,stem} = MINSL * FR_{g,leaf} \quad (10.13)$$

Step 6. Remaining assimilates ($FR_{g,rest}$), if any, can be used for additional structural growth, or be stored as carbohydrate reserves. If sinks are too weak or too small, (part of) $FR_{g,rest}$ is considered lost (c.f. Alexander, 1973; Sawada et al., 1999).

$$FR_{g,rest} = 1.0 - FR_{g,root} - FR_{g,genr} - FR_{g,stem} - FR_{g,leaf} \quad (10.14)$$

Step 6.1. Partitioning to reproductive organs is arbitrarily adjusted by adding a proportional part of $FR_{g,rest}$ to $FR_{g,genr}$:

$$FR_{g,genr} = FR_{g,genr} + FR_{g,genr} * FR_{g,rest} \quad (10.15)$$

Step 6.2. If the amount of stored reserves, expressed as a fraction of structural stem biomass (S_{stem}, kg ha^{-1}) is below a critical low level MINLAB (kg kg^{-1}), the remaining part of $FR_{g,rest}$ is allocated to the labile storage pool:

$$\text{If } (S_{labst}/S_{stem} < MINLAB) \text{ then } FR_{g,labst} = FR_{g,rest} \quad (10.16)$$

Step 6.3. Else, if water is sufficiently available (tentatively defined as $TR_a/TR_m > 0.8$), a portion FRLIB (see equation 10.10) of $FR_{g,rest}$ is used for additional stem growth:

$$\text{If } (TR_a/TR_m > 0.8) \text{ then } FR_{g,stem} = FR_{g,stem} + FR_{g,rest} * FRLIB \quad (10.17)$$

Step 6.4. Else, if ($S_{root} < S_{root,max}$) then $FR_{g,root} = FR_{g,root} + FR_{g,rest}$ (10.18)

Step 6.5. If the amount of stored reserves in the stem is below a critical high level MAXLAB (kg kg^{-1}), there is “available space” for storage of sugar reserves in the stem and any remainder of $FR_{g,rest}$ is allocated to the storage pool:

$$\text{If } (S_{labst}/S_{stem} < MAXLAB) \text{ then } FR_{g,labst} = FR_{g,rest} \quad (10.19)$$

Step 6.6. If, after all this, $FR_{g,rest}$ has not been completely allocated, AAL is adjusted; i.e., it is assumed that the value calculated in equation 10.9 was too high. Reallocation of these assimilates to the storage pool would double conversion losses.

Step 7. Gross assimilate allocation rates GAA_{org} (kg ha^{-1} day^{-1}) are calculated as:

$$GAA_{org} = AA * FR_{g,org} \quad (10.20)$$

where subscript “*org*” stands for ‘genr’, ‘leaf’, ‘root’, ‘stem’ or ‘labst’.

Step 8. Basic values of net assimilate allocation rates, NAA_{org} (kg ha^{-1} day^{-1}), are calculated by subtracting maintenance respiration from gross assimilation rates:

$$NAA_{org} = GAA_{org} - MRR_{org} \quad (10.21)$$

Values of MRR_{org} are calculated as indicated in table 10.1.

Step 9. Dry mass increments DWI_{org} (kg ha^{-1}) during time interval Δt are calculated as follows:

If $NAA_{org} \geq 0.$ then $DWI_{org} = NAA_{org} * EC_{org} * \Delta t$ (10.22)

However, if $NAA_{org} < 0.$ then different organs are treated differently:

Step 9.1. Variable CHECKLAB ($kg\,ha^{-1}$) is introduced to monitor the total amount of assimilates potentially available to cover possible excessive maintentance losses. Its initial value is calculated by:

$$CHECKLAB = EC_{lib}*S_{labst} + \Delta t*(NAA_{labst} - AAL) \quad (10.23)$$

Step 9.2. Reproductive organs and stems: If calculated gross assimilate allocation is insufficient to satisfy the maintenance needs of reproductive organs or stems, then the difference is covered by stored reserves. Reproductive organs are assumed to have priority over stems. If the storage pool is empty, then DWI_{org} becomes negative:

If $NAA_{org} < 0.$ then
$CHECKLAB = CHECKLAB + \Delta t*NAA_{org}$; $DWI_{org} = 0.$ (10.24)
If(CHECKLAB< 0.) then
DWI_{org}= CHECKLAB; CHECKLAB=0. (10.25)

Step 9.3. Leaves and roots: possible excess maintenance losses are not covered by carbohydrate reserves. The crop adjusts itself by consuming structural matter from these organs:

If $NAA_{org} < 0.$ then $DWI_{org} = NAA_{org} * \Delta t$ (10.26)

Step 9.4. Labile storage pool: Increase or decrease of stored carbohydrate reserves during Δt is calculated by bookkeeping:

If $(CHECKLAB-EC_{lib}*S_{labst} \geq 0.)$ then
$DWI_{labst} = (CHECKLAB-EC_{lib}*S_{labst})* EC_{labst}$ (10.27)
else $DWI_{labst} = CHECKLAB/EC_{lib} - S_{labst}$ (10.28)

Note that equations 10.25 and 10.26 implicitly assume a "conversion efficiency" of 1. when DWIorg < 0.

10.6 Comparison of model results with growth experiments on soybean and sugarcane of the study regions

10.6.1 Material and methods

A first test of the model was made by comparing model results with data from growth experiments with soybean in the Passo Fundo region and with sugarcane in the Araras region.

Crop growth data

The soybean growth experiment was carried out in co-operation with EMBRAPA/CNPt on one of their experimental fields in Passo Fundo (area 7 in figure 3.4). Three cv's, commonly planted in South and South East Brazil, were analysed; viz. Davis, IAS-5 and BR-4. The soil in the field is an allic, very fine clayey Dark Red Latosol (soil profile description is available from the author). In previous years, the field had been planted to oats, wheat, rapeseed, barley or flax in winter, in rotation with soybean or sorghum in summer. The preceding oats crop had been harvested a few weeks before the planting of the soybean crop followed in this study. The results for cv Davis were also used by Siqueira & van den Berg (1991) alongside yield data from previous years, for testing of the SOYGRO model of Jones et al. (1989).

The study field was subdivided in 9 plots of 10 x 20 m, as shown in figure 10.4. On November 10, 1989, seeding was done by direct drilling in the oats stubble to the conventional density of some 20 seeds per m in rows that were 0.5 m apart. In each plot, samples containing all shoots along 1 m row (as measured on the ground) were taken in triplicate. This was done with intervals of some 15 days, starting 24 days after planting (d.a.p.), until harvest maturity (stage R8 of Fehr et al., 1971). Fresh weights of leaf blades, petioles, stems, pods and seeds were determined and dry masses were determined on sub-samples, dried to constant weight at 60°C. The leaf areas of the sub-samples were determined with an optical leaf area meter before drying. Dry organ masses per ha, specific leaf areas and leaf area indexes were calculated for each plot. Some soybean leaf borers (*Anticarsia gemmatalis*) were observed in the first week of January 1990. This potential problem was timely controlled by spraying the crop with a suspension of crushed dried borers infected with the nuclear polyhedrosis virus (*Baculovirus anticarsia*).

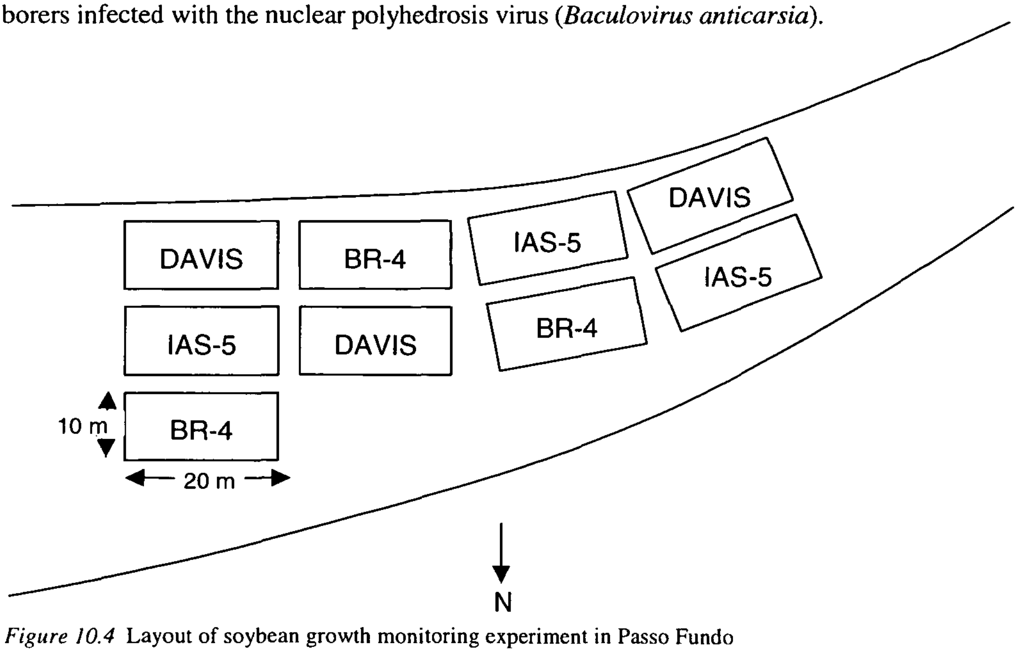


Figure 10.4 Layout of soybean growth monitoring experiment in Passo Fundo

Model results for sugarcane were compared with data of Machado et al. (1982) and of Pereira & Machado (1986). They monitored the growth of sugarcane (c.v. NA-5679) on strongly weathered dark red clay soils in Piracicaba (± 45 km south-west of Araras) and Araras. The Piracicaba cane was planted on March 28, 1978. Monitoring started on October

8, 1978 (133 d.a.p.). The Araras cane was planted on October 15, 1981 and monitoring started on December 15, 1981 (61 d.a.p.). In both experiments, the surface area of leaf blades and the dry masses of leaf blades and of stems + leaf sheaths were determined. The distance between plant rows was 140 cm, as normally used in São Paulo State. The cited works do not provide data on the amount of plant material and stalk density in rows.

Weather data

Weather data for the period of the crop growth experiments were obtained from official meteorological stations within 500 m of the experimental sites, except for the Araras sugarcane experiment, for which weather data were used from Limeira ($\pm$ 10 km south of the experimental site). Observed daily values of precipitation, minimum temperature and maximum temperature were used. Values for air humidity, wind speed and hours of sunshine were estimated from monthly averages.

Estimation of model parameters

Most crop parameters were derived from published literature. Different sources suggest quite different values for some items, whereas no values were encountered for others. Therefore, some coefficients were inferred from the monitoring experiments or adjusted to improve the fit between model results and observed data. It follows that the growth curves in this study are not an independent validation set.

Parameter estimation for soybean was first done for c.v. Davis. Much information on phenological development of this c.v. could be derived from J.W. Jones et al. (1991), whose relations had already shown to be in good agreement with the results of Siqueira & Van den Berg (1991). Most of their SOYGRO growth phases could be transformed to RDS as defined in section 10.5.1. Their piecewise linear relations between average temperature (T_{24h}) and C(I) during juvenile development and during maturation were adopted to describe phenological development while RDS<1 and RDS>2 (see figure 10.5). The relations for their phase 1 (from planting to emergence) was simplified by setting this period to a fixed duration of 8 days. The photothermal time concept, where C(I) of equation 10.6 is obtained by multiplication of a correction factor for photoperiod (C_{DL}) with another factor for night temperature (C_{Tnight}), was applied to their phases 4 to 10 ($1 \leq RDS \leq 2$), but with the following simplifications:

- The correction factor for the effect of photoperiod (C_{DL}) on phenological development was estimated according to a linear relation. A comparison with the inversely proportional relation of J.W. Jones et al. (1991) is shown in figure 10.6. Note that the photoperiod never exceeds 14.5 h. at the latitudes of the study regions.
- the relation between night temperature and C_{Tnight} was simplified as shown in figure 10.7.
- the same relations for C_{DL} and C_{Tnight} were used for their stage 5 (flower induction to flower appearance), as for their stages 4 and 6-10, i.e. without the additional correction for T_{24h}.
- partitioning to reproductive organs was assumed to start effectively at the end of their phase 6 (first pod > 2 cm in length);

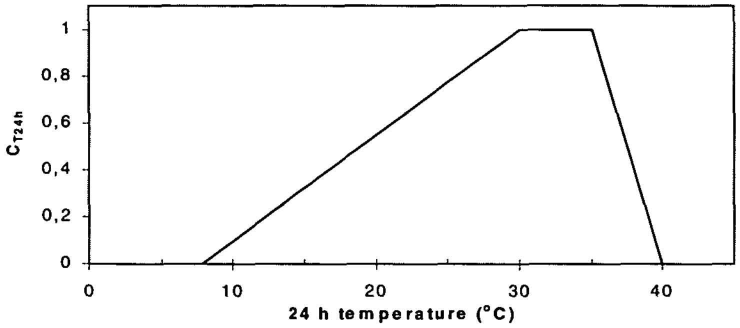


Figure 10.5 Temperature correction factor (C_{T24h}) for soybean phenological development rate during juvenile phase (RDS<1) and maturation (2<RDS<3), as adopted from J.W. Jones et al. (1991).

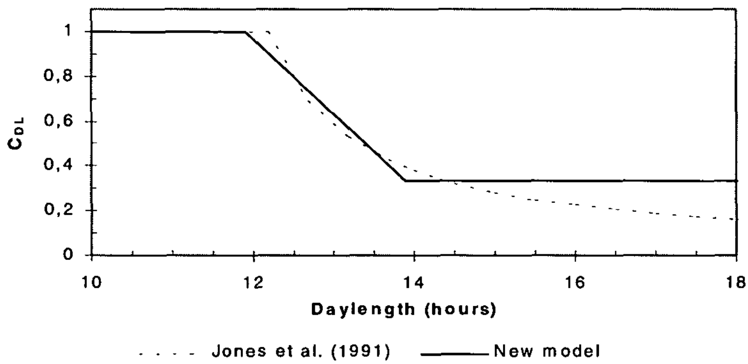


Figure 10.6 Photoperiod correction factor (C_{DL}) for soybean phenological development rate during the photoperiod sensitive phase ($1 \leq RDS \leq 2$), as suggested by J.W. Jones et al. (1991), and adapted in the model

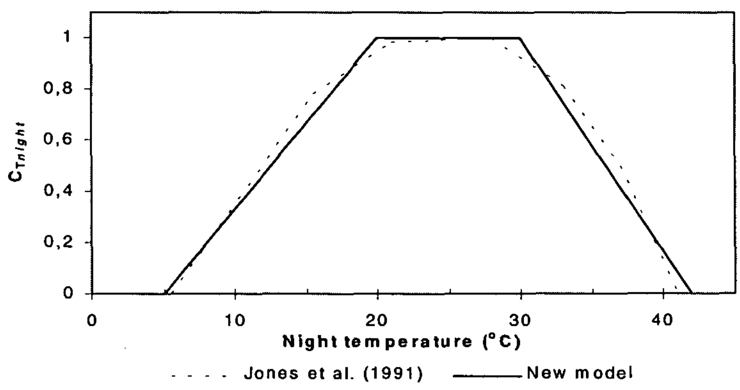


Figure 10.7 Night temperature correction (C_{Tnight}) for soybean phenological development rate during the photoperiod sensitive phase ($1 \leq RDS \leq 2$) suggested by J.W. Jones et al. (1991) and adapted for the model of this study

- the RDS at which partitioning to reproductive organs becomes 1. (not considered by J.W. Jones et al., 1991) was determined by adjusting the parameter concerned between their values for last leaf expansion and harvest maturity.

The tentative function that relates remobilization from the labile pool to T_{24h} (equation 10.10) is shown in figure 10.8

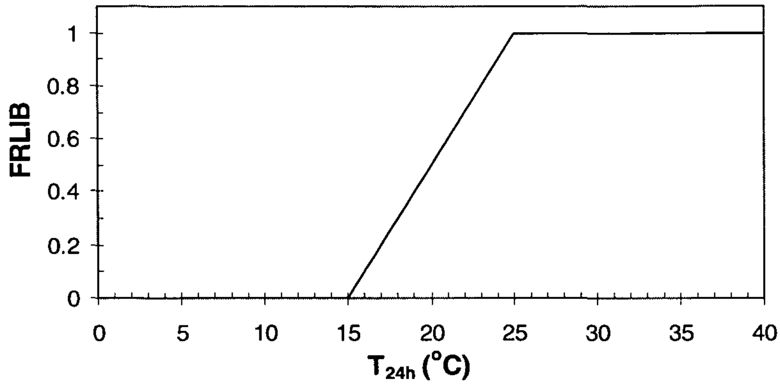


Figure 10.8 Tentative correction factor (FRLIB) on the remobilization rate of stored carbohydrate reserves as function of temperature (T_{24h}) under optimum water availability conditions

The parameter values obtained for c.v. Davis were taken as a starting point in the determination of those of IAS-5 and BR-4. First, RDS related parameters were adjusted within the range of values mentioned for several c.v.'s by J.W. Jones et al. (1991). It was checked then if the fit could be improved substantially by adapting any of the other parameters. It was felt that exhaustive calibration trials to obtain exact fits between model results and actual growth curves would not be justified.

Water retention characteristics and θ_{2d} values for the soybean trials were obtained by sampling directly adjacent to the experimental field (see methodology in Chapters 6 and 7). Soil-water data determined on soil from 45 cm depth were assumed to be representative for the rooted surface soil compartments.

Parameters related to phenological development of sugarcane were derived from Pereira et al. (1983) who studied flowering of cv. NA5679 in Araras. Flowering is favoured by high night temperatures and low day temperatures during the inductive period (decreasing day length of 12-12.5 h). All occurrences of flowering plants reported by Pereira et al. (1983) are discriminated from non-flowering plants by 13 nights with $T_{min} \geq 18°C$ during the inductive period. However, Pereira et al. (1983) suggest that 10 nights may be sufficient to induce flowering if day temperatures are relatively low (maximum temperature $T_{max}<31°C$). After induction, it takes another 7 to 10 weeks before flowers actually appear. Since sugarcane flowering and its effect on yield and cane quality remain controversial subjects, and many farmers apply chemical substances to prevent flowering, the model merely indicates the possibility of flowering when $\geq$8 days with $T_{max}<31°C$ and $T_{min} \geq 18°C$

occur during the inductive period followed by at least 70 days until harvest. Physiologic consequences of flowering are not taken into account however, i.e. the model assumes that vegetative growth proceeds normally. Results of both growth monitoring experiments (Piracicaba and Araras) were used to adjust other parameters, including those for soil water relations and initial carbohydrate reserves used during germination.

Biomass partitioning fractions derived from the model results were calculated as follows, in analogy with equation 10.1:

$$FR_{org} = DMI_{org}/(DMI_{root} + DMI_{leaf} + DMI_{stem+labst} + DMI_{repr}) \qquad (10.29)$$

where dry mass increments (DMI_{org}) are cumulative values ≥ 0, over periods of 10 days.

10.6.2 Results

Soybean

Harvest maturity as defined by Fehr et al. (1971) was reached on April 12, 1990 (152 d.a.p) for IAS-5, on April 22 for BR-4 and on April 23 (163 d.a.p.) for Davis. The total amounts of precipitation gauged during the growing periods were 819 mm for IAS-5 and 865 mm for Davis and BR-4.

Table 10.2 lists crop parameter values for soybean c.v. Davis and comments on how these values were obtained. The same set was used for IAS-5 and BR-4, except for the parameters to calculate (a) phenological development rates, (b) the onset of pod growth and (c) the end of assimilate allocation to vegetative organs. These parameter values were obtained by calibration, adjusting model results with observed data. It follows that during vegetative growth the model results are exactly the same for the three c.v.'s considered.

A serious problem for parameter estimation by calibration was the strong sensitivity of the model for (the tolerance to) excess water expressed by parameter $U_{r,wet,min}$ (see appendix 2, figure A2.1). Indeed, the crop suffered visibly from excessive wetness during the field trials and formed adventitious roots at the soil surface. Examination of a soil profile revealed clear evidence of degradation (soil compaction) and roots were concentrated on ped faces. $U_{r,wet,min}$ = 0.14 gave the best fit, but it is realised that the methods used to describe soil air dynamics and plant response to aeration are a weak representation of the complex processes involved. Indications of water shortage were neither observed in the field nor calculated by the model.

Biomass values of different crop components, observed and simulated after calibration, are presented in figure 10.9, together with recorded minimum and maximum temperatures and precipitation over the growing period. In general, the model results correspond very well with the observed data, but some interesting discrepancies appear after the onset of reproductive growth.

Table 10.2 Crop parameter values used for simulation of soybean (c.v. Davis) and their origin

Feature	**value**	**Source, remarks**
Duration seeding to emergence (days)	8	Observed value
Type of carbon cycle:	C3	
Leaf longevity (d°C; base temperature = 0°C)	800	Hanway & Weber (1971), cited by Heemst (1988): about 40 days at 20°C; Boon-Prins et al. (1993) assume 23 d at 35°C; Driessen & Konijn, (1992) suggest 520 d°C, with base temperature at 0°C.
Reference temperature range where maximum photosynthesis is possible (°C)	22-39	free interpretation of several works cited by Heemst (1988).
Minimum reference temperature for maintenance respiration; see Driessen & Konijn (1992, p. 127) (°C)	10	Driessen & Konijn (1992).
Lower crit. temperature for remobilization of stored reserves (°C)	15	First guess
Lower opt. temperature for remobilization of stored reserves (°C)	25	First guess
Maximum remobilization rate of stored reserves (kg ha^{-1} day^{-1})	50	First guess (FRAAMXE, equation 10.13 was set to 1.)
Max. expansion rate of rooted depth (cm.d^{-1})	3.0	Stone et al., 1976 (cited by Penning de Vries et al., 1989); Mitchell & Russell, 1971: 150-183 cm in 102 days.
Max. rooting depth (cm)	170	Stone et al., 1976 (cited by Penning de Vries et al., 1989); Mitchell & Russell, 1971: 150-183 cm
Rooting depth at emergence (cm)	15	
Crop number (to calculate soil water depletion fraction)	5	Driessen (1986); corresponds to group 4 of Allen et al (1998)
Tolerance to water logging ($U_{r,wet,min}$)	0.14	curve fitting with results of field trial; see text.
Specific leaf area (m^2 kg^{-1})	30	average value for leaf blades in trial (Penning de Vries et al, 1989, p. 100: 25 m^2 kg^{-1}); Bhagsari et al. (1977): 30-33 m^2 kg^{-1} for cv. Davis
Initial light (PAR) use efficiency (kg CO_2 ha^{-1} h^{-1} J^{-1} m^{-2} s^{-1})	0.45	Penning de Vries et al., (1983, p. 32): 0.48; Harley et al. (1985): 0.42; Boon-Prins et al. (1993) adopted 0.40
Light (PAR) extinction coefficient (k_e)	0.8	Heemst (1988); this value was also adopted by Boon-Prins et al. (1993).
Maximum wind turbulence coefficient	1.1	Driessen & Konijn (1992), Doorenbos & Kassam (1979): 1.0 - 1.15

Table 10.2 (continued)

Feature	value	Source, remarks
Maintenance requirements at reference temperature ($kg\ CH_2O\ kg^{-1}\ day^{-1}$)		Maintenance respiration is calculated according to Driessen & Konijn (1992).
leaves	0.03	Generic value suggested by Penning de Vries & Laar (1982) and cited by Heemst (1988) and used by Boon-Prins et al. (1993); Driessen & Konijn (1992) suggested 0.015 which corresponds with values for other crops suggested by Penning de Vries et al. (1989, p. 51 and 52); 0.03*30/44 was adopted for soybean by Penning de Vries et al. (1992), p. I-5, line 573.
roots	0.01	Driessen & Konijn (1992), corresponds with 0.015*30/44 suggested by Penning de Vries et al. (1989, p. 52) and the generic value of 0.01suggested by Penning de Vries & Laar (1982) and cited by Heemst (1988) and used by Boon-Prins et al. (1993).
structural stem material (+ petioles)	0.015	Driessen & Konijn (1992, p. 124), corresponds with generic value suggested by Penning de Vries & Laar (1982) and cited by Heemst (1988) and used by Boon-Prins et al. (1993), but smaller values (0.007-0.014 in dependence of age) were suggested by Penning de Vries et al. (1989, p. 53).
reproductive organs	0.01	Heemst (1988), suggest 0.017, citing Penning de Vries et al. (1983), but I could not derive this value from the cited reference. 0.017 was adopted by Boon-Prins et al. (1993). Penning de Vries et al. (1989, p. 53) suggest for crops in general: 0.01 - 0.014; no maintenance for mass exceeding 1000 kg ha^{-1}
stored reserves (starch)	0	Suggested by Penning de Vries et al. (1989, p. 210, line 89)
Conversion efficiencies		Values are derived from Penning de Vries et. al (1989, p. 64). Calculated from biomass composition assuming N provided by Rhizobia fixation in root nodules.
leaves	0.593	1/1.687, representative value for leaves of leguminous crops.
roots	0.652	1/1.534, representative value for roots of leguminous crops.
stems (+ petioles), excl. stored reserves	0.610	Penning de Vries et al. (1989), p. 63-64; calculated from biomass composition, assuming 10% of stem material (see their table 11) are stored reserves. These were excluded from calculation).
pods (shells + seed)	0.463	1/2.161
formation of stored reserves (starch)	0.852	=0.947*0.9 Penning de Vries et al. (1989), 0.947: 5.3% energy content of glucose lost by passage accross 1 membrane; 0.9: (g starch/C)/(g glucose/C).
remobilization of stored reserves	1.052	=0.947*1.111 Penning de Vries et al. (1989).

Table 10.2 (continued)

Feature	value	Source, remarks
Parameters that govern assimilate partitioning		
Maximum LAB/(structural stem) ratio (MAXLAB)	0.25	Hanway & Weber, 1971; cited by Penning de Vries et al. (1989, p. 47). Derived as 0.25 = 0.18*1.1/(1-0.18*1.1).
Critical minimum LAB/(structural stem) ratio (MINLAB)	0.25	Guess: MINLAB=MAXLAB
Minimum $FR_{g,stem}/FR_{g,leaf}$ ratio (MINSL, equation 10.13)	0.45	Calibration for 2nd observation (39 d.a.p.) in growth experiment.
Initial partitioning to roots ($FR_{g,root,max}$)	0.5	Adopted from sources of figure 10.1 This value may be overestimated however. Most consulted works (e.g. Mayaki et al., 1976; Sivakumar et al., 1977) suggest that root growth lags behind leaf growth.
Maximum root mass (kg ha^{-1})	1500	Maximum value reported by Mayaki et al. (1976): 2895 kg ha^{-1}; Sivakumar et al. (1977): 584 kg ha^{-1}; Note: original observations are on surface area << $1m^2$
Phenological development		
RDS at which partitioning to reproductive organs starts	1.374	Derived from J.W. Jones et al. (1991); see explanation in text
RDS at which partitioning to vegetative organs stops	1.60	Calibration
Critical and optimum values for phenologic development		See text and figures 10.5, 10.6 and 10.7
Phase 1, T_{24h} (°C),	7.8, 30, 35, 40	Order: low critical., low optimum, high optimum, high critical
Phase 2, T_{night} (°C)	5, 20, 30, 42	
Phase 2, photoperiod (h.day^{-1})	0, 0, 11.9, 14.9	
Phase 3, T_{24h} (°C),	7.8, 30, 35, 40	
Maximum phenological development rates (day^{-1})		
Phase 1	1/9	Derived from J.W. Jones et al. (1991); see explanation in text
Phase 2	1/62.59	
Phase 3	1/8.5	

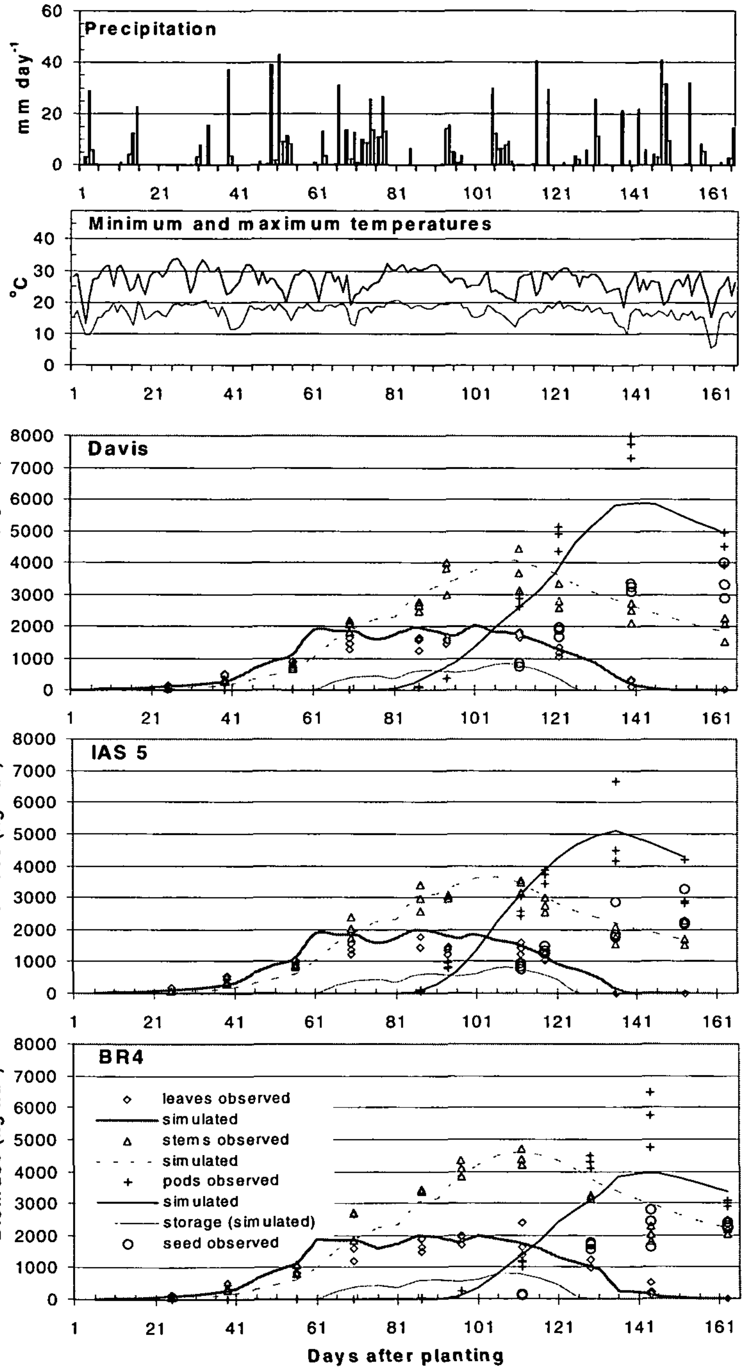


Figure 10.9 Weather data and observed and simulated biomasses of different soybean crop components after calibration for the crop monitoring experiment. Day 1 is November 10, 1989

The observed decrease in pod mass during maturing was considerably stronger than calculated, especially for Davis and BR-4. The decrease in the observed data could be attributed solely to loss of shell weight. Seed weights remained constant or increased. The number of pods observed decreased gradually, from an average 680 per m row at 112 d.a.p. to 590 at harvest maturation for Davis. Similar trends were observed for the other c.v.'s. Unfortunately, the seed numbers were only counted at the last harvest, and aborted pods were not sampled. In most cases, overestimates in pod mass coincide with underestimates in the mass of stems + carbohydrate reserves, and *vice versa.* Note that there remains a possibility that the observed pod mass values of the one-but-last samples may be overestimated, if the oily samples were insufficiently dried.

Assuming the same crop and weather conditions but ignoring soil aeration as a stress factor (by setting $U_{r,wet,min}$ to 1.0) resulted in (simulated) very fast canopy closure and an extremely large stem biomass as shown in figure 10.10a for c.v. Davis. In reality this is not likely to happen for one or more of the following reasons (1) lodging, which is common in soybean grown under optimal conditions (Reicosky & Heatherly, 1990); (2) a decrease in assimilation rate resulting from sink weakness between the moment of canopy closure and the onset of seed filling (c.f. Brun, 1978, Shibles et al., 1989); (3) relative leaf expansion rate during initial growth may be constrained by the sink capacity of leaves; and/or (4) errors in parameter values. Possible effects of relative leaf expansion constraints were tested according to the approach suggested by Goudriaan & van Laar (1994). This was done by assuming zero leaf expansion rate at temperatures $\leq$ 7.8°C and 0.12 $m^2 m^{-2} day^{-1}$ at $\geq$30°C, and a linear increase between these temperatures. The results of this exercise, shown for c.v. Davis in figure 10.10b, are not very different however from those of figure 10.10a. An example of how apparently realistic results can be obtained with different parameter values is given in Figure 10.10c. The same settings are used as in figure 10.10b, except that (1) leaf longevity was set to 520 day °C as suggested by Driessen & Konijn (1992) instead of the 800 day °C derived from the data presented by Van Heemst (1988) and Boon-Prins et al. (1993); and (2) the value of RDS when assimilate allocation to vegetative organs becomes nil was increased.

Biomass partitioning fractions derived from the model results of figure 10.9 (water- and aeration-limited growth) are given in figure 10.11. The trivial trends of the indicative functions of figure 10.1 are still present, but the model results suggest considerable fluctuations. FR_{stem}, with values >0.6 just before the onset of pod growth, is large in comparison with the curves of figure 10.1, but commensurate with the value of 0.72 suggested by Wilkerson et al., (1983) for use in the SOYGRO model.

Sugarcane

Table 10.3 lists crop parameter values used in the calculations for sugarcane, c.v. NA5679, and comments on how these values were obtained. Besides these parameters, soil water parameters and initial carbohydrate reserve values in the model were adjusted to obtain a good fit with the reported values. The initial value of 1200 kg ha^{-1}, estimated for the Piracicaba experiment seems well in line with current sugarcane management practices in the study regions. However, the inferred initial value of 250 kg ha^{-1} for the Araras experiment is very small. Considering the well-drained soil and the good weather conditions

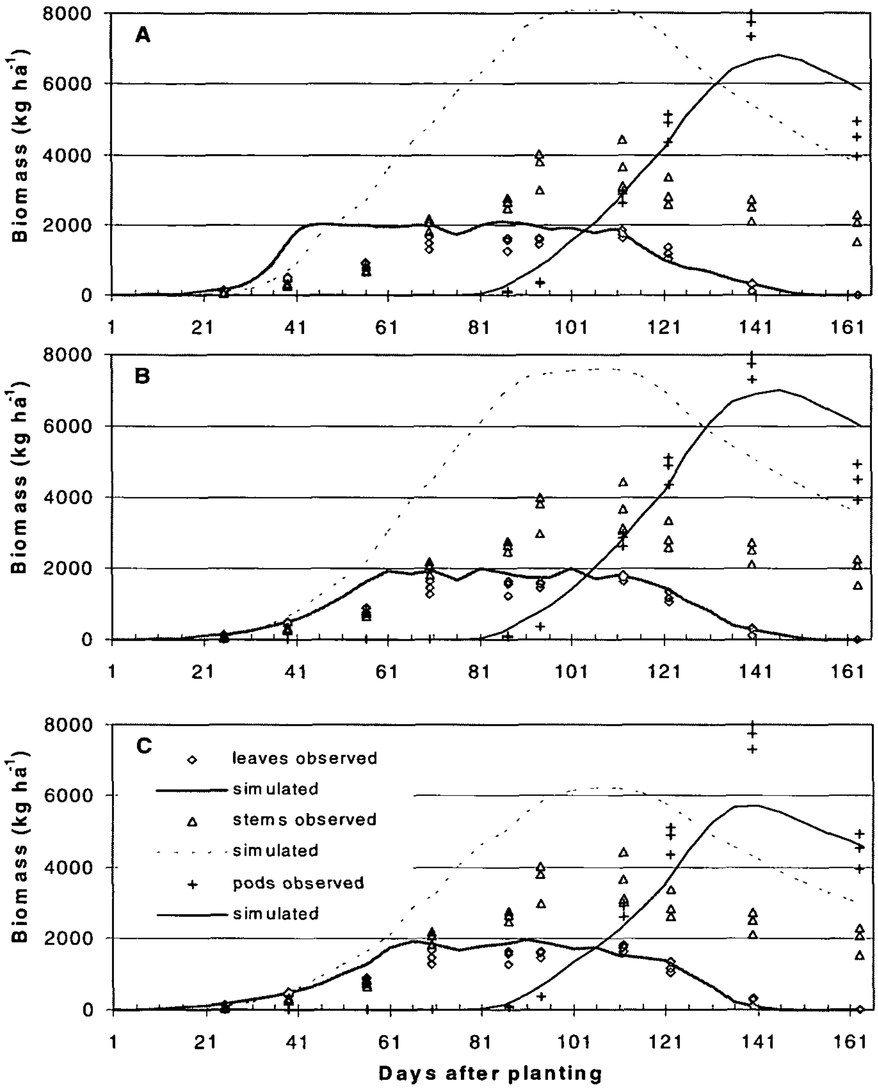


Figure 10.10 Observed and simulated biomasses of different soybean (c.v. Davis) crop components, assuming no aeration stress. (a) leaf area expansion not restricted in model; (b) leaf area expansion restricted by 0.12 $m^2\,m^{-2}$ under optimum temperature conditions; (c) as (b), and leaf longevity set to 520 day°C

during initial growth, either severe nutrient shortage or an error in the planting date reported by Pereira & Machado (1986) may have occurred.

Observed and simulated sugarcane growth data are compared in figures 10.12 (Piracicaba) and 10.13 (Araras), together with recorded minimum and maximum temperatures and precipitation. Total amounts of precipitation during the growing periods were, 1488 mm (Piracicaba 78/79) and 2216 mm (Araras, 81/82). Note that the growing

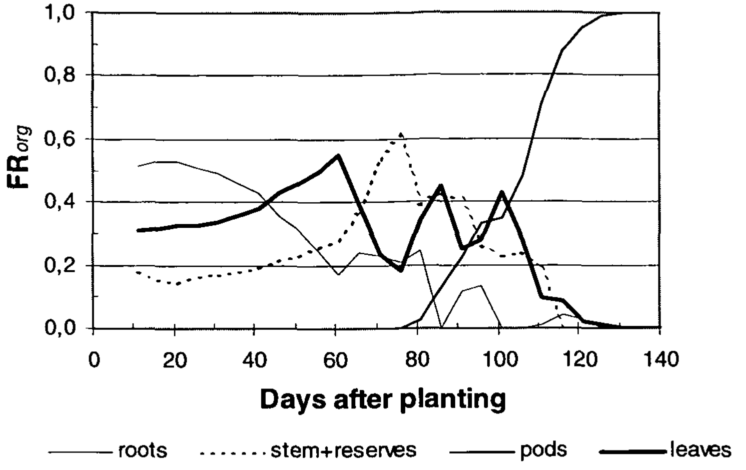


Figure 10.11 Soybean (c.v. Davis) biomass partitioning fractions derived from model results (water and aeration limited growth)

conditions for the two sugarcane crops were very different.

Figures 10.12 and 10.13 suggest a good correspondence between simulated and observed total above ground living biomass, but the model overestimated the leaf area index for both experiments. Note that observed LAI values are very small, especially in the Araras experiment (figure 10.13). Leaf growth may have been affected by shortage of nutrients (e.g. nitrogen), but better fits could also be obtained by simultaneously increasing light use efficiency and the sensitivity to water shortage. The latter was also suggested by Nable et al. (1999). Simulated potential growth curves (not limited by water shortage) are included in figures 10.12 and 10.13. For the Piracicaba experiment, the curves for constraint free growth are very close to the ones for water-limited growth, as explained by the high and well distributed rainfall. Differences in simulated water limited and potential growth are considerable for the Araras experiment with less and more poorly distributed rainfall. In both cases, simulated relative leaf area expansion did not reach extremely great values.

Partitioning fractions for sugarcane derived from the model results are given in figure 10.14. The general trends and values fall within the ranges of data mentioned by Van Heemst (1988) and Keating et al. (1999), but again, the model results suggest considerable fluctuations. Note that, on average, partitioning to leaves is considerably smaller in the high yielding Piracicaba experiment than in the poor yielding Araras experiment, even though simulated LAI is smaller in the latter. The reason is (simulated) greater leaf turnover in the Araras experiment, with accelerated leaf senescence due to water shortage during frequent dry spells, followed by short periods with sufficient water, during which a large fraction of assimilates is allocated to the leaves to restore leaf area.

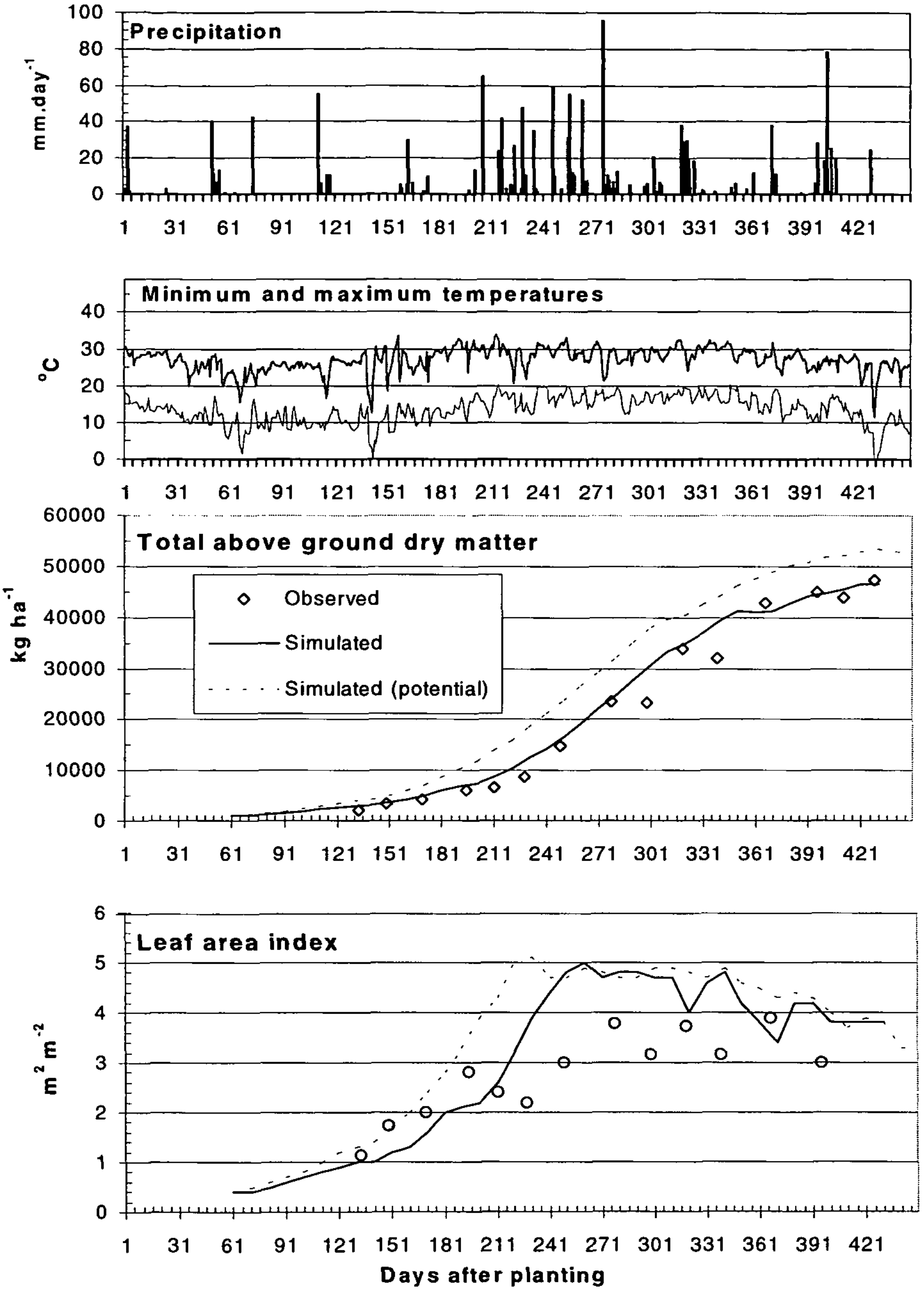


Figure 10.12 Weather data and reported and simulated data of (a) total above ground living biomass and (b) leaf area index for growth monitoring experiment of Pereira & Machado (1986) in Piracicaba (1978/1979). Day 1 is March 28th, 1978

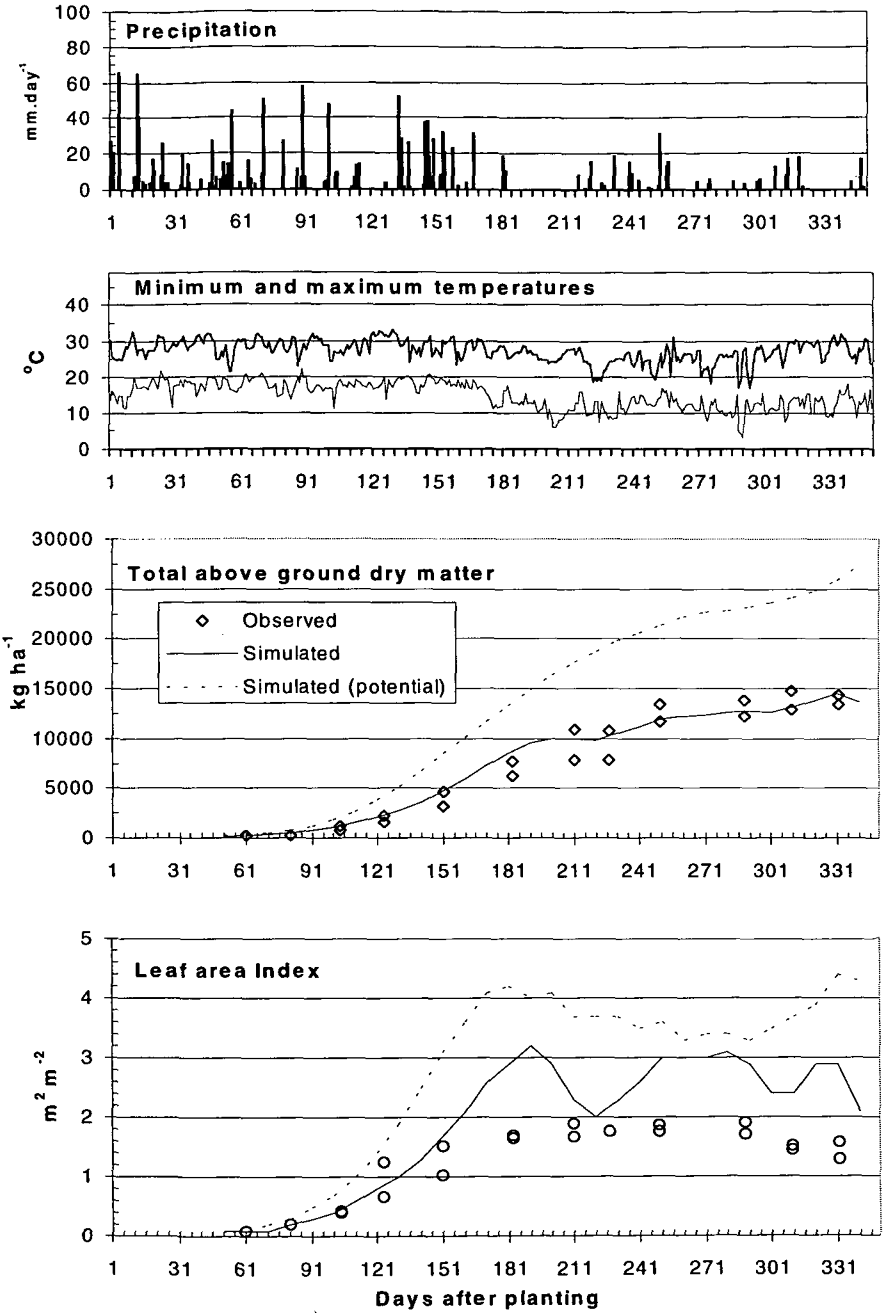


Figure 10.13 Weather data and reported and simulated data of (a) total above ground living biomass and (b) leaf area index for growth monitoring experiment of Pereira & Machado (1986) in Araras (1981/1982). Day 1 is October 15th, 1981

Table 10.3 Crop parameter values used for simulation of sugarcane (c.v. NA5679) and their origin.

Feature	value	Source, remarks
Type of carbon cycle:	C4	
No days from planting/ratoon to emergence	10	
Leaf longevity (temperature sum, d°C)	2000	Driessen & Konijn (1992): 900 d°C; Ayres (1936): 90-105 days; Varlet-Grancher et al. (1981): ±135 days; Irvine (1983): 60-75 days (average)
Optimal temperature range for photosynthesis (°C)	24-35	
Minumum temperature for photosynthesis (°C)	10	
Maximum remobilization rate of stored carbo-hydrates	10 % but ≤ 50 kg $ha^{-1}day^{-1}$	Guess
Expansion rate of rooted depth ($cm.d^{-1}$)	1	Gascho & Shih (1983): elongation of set roots: 20 cm in 11 days; shoot roots: 7.5; Wood & Wood (1967): root penetration up to 210 cm depth in 189 days; Ball-Coelho et al., (1992)
Max. rooting depth (cm)	200	Gosnell & Thompson (1965): water extraction in one soil down to at least 2.2 m.
Rooting depth at emergence (cm)	40	large value to compensate for accelerated root expansion during initial growth.
Maximum root mass (kg ha^{-1})	8000	Inforzato & Alvarez (1957): 804 $g.m^{-2}$ over 210 cm depth; Ball-Coelho et al., (1992)
Crop group for determination of soil water depletion fraction	5	Driessen (1986); corresponds to group 4 of Allen et al., (1998)
Tolerance to water logging	-	Not relevant for well drained permeable soils of the study regions
Effective specific leaf area (m^2 kg^{-1})	6.0	Area leaf blades/(mass leaf blades+sheaths) based on value of 10.0 for leaf blades of cv. NA5679 (Machado et al., 1982) and dry mass leaf/sheath relation of 1/2, for NA5679 at different ages, observed in Assis study fields.
Initial light (PAR) use efficiency (kg CO_2 ha^{-1} h^{-1} J^{-1} m^2)	0.45	Hartt & Burr (1967): 0.26; Waldron et al. (1967): 0.29; Bull (1969): 0.30; Varlet-Grancher et al. (1981): 0.51
Light (PAR) extinction coefficient (k_e)	0.50	Machado et al. (1985), cv NA5679; Varlet-Grancher & Bonhomme (1979): 0.48
Maximum wind turbulence factor	1.2	Driessen & Konijn (1992), based on Doorenbos & Kassam (1979): 1.05-1.3

Table 10.3 (continued)

Feature	value	Source, remarks
Maintenance requirements at reference temperature ($kg\ CH_2O\ kg^{-1}\ day^{-1}$)		Determination of reference temperature as 10 day moving average of T24h was slightly modified from PS123: Tref(runday) = Tref (runday-1)*0.9 + T24h(runday)*0.1.
leaves	0.020	O_2 absorption data from Hieke et al. (1990) suggest average dark respiration of leaf cuttings (6 c.v.'s): 0.02 kg CH_2O kg^{-1} day^{-1} at 25°C. Glover (1973) reported a much lower value (0.005), by estimating leaf respiration from CO_2 produced in the dark by whole plants, minus CO_2 produced by stalks with detached leaves.
roots	0.01	Driessen & Konijn (1992), corresponds with 0.015*30/44 suggested by Penning de Vries et al. (1989, p. 52) and the generic value of 0.01suggested by Penning de Vries & Laar (1982) and cited by Heemst (1988)
stems (+ petioles)	0.004	Hieke et al. (1990) average CH_2O consumption for 6 c.v.'s, cuttings of mature stems at 25°C: 0.0035 kg kg^{-1} day^{-1}; O_2 consumption suggests 0.004. Glover (1973): 0.003 kg CH_2O kg^{-1} day^{-1} at 25°C, calculated from CO_2 production of whole stalks.
reproductive organs	-	not considered in model
assimilate reserves	0.002	Guess. *Some energy is necessary to maintaintain concentration gradients because some* leakage occurs from vacuoles (Alexander, 1973)
Conversion efficiencies		
leaves	0.684	Penning de Vries et al. (1989)
roots	0.693	Penning de Vries et al. (1989)
stems (exluding stored sucrose reserves)	0.654	Based on Penning de Vries et al. (1989, assuming 20% of given composition are sucrose reserves).
reproductive organs	-	not considered in model
assimilate reserves (sucrose)	0.900	=0.947*0.95 Penning de Vries et al. (1983, p. 44, eq. 9; 1989).
remobilization of stored reserves (sucrose)	0.997	=0.947/0.95 Penning de Vries et al. (1989). 0.95: (g sucrose/ C)/(g glucose/ C).
Maximum LAB/STEM ratio (MAXLAB)	1.5	Maximum value of soluble solids (i.e. sacharose+reducing sugars + some other organic
Critical minimum LAB/STEM ratio (MINLAB)	1.5	and mineral dissolved substances) in sugarcane stalks among data on cv. Na5679 provided by Usina São João estate in Araras.
Minimum $FR_{g,stem}/FR_{g,leaf}$ ratio (MINSL, equation 10.13)	0.45	calibration
Initial partitioning to roots ($FR_{g,root,max}$)	0.3	tentative Driessen & Konijn (1992); Keating et al. (1999): 0.33

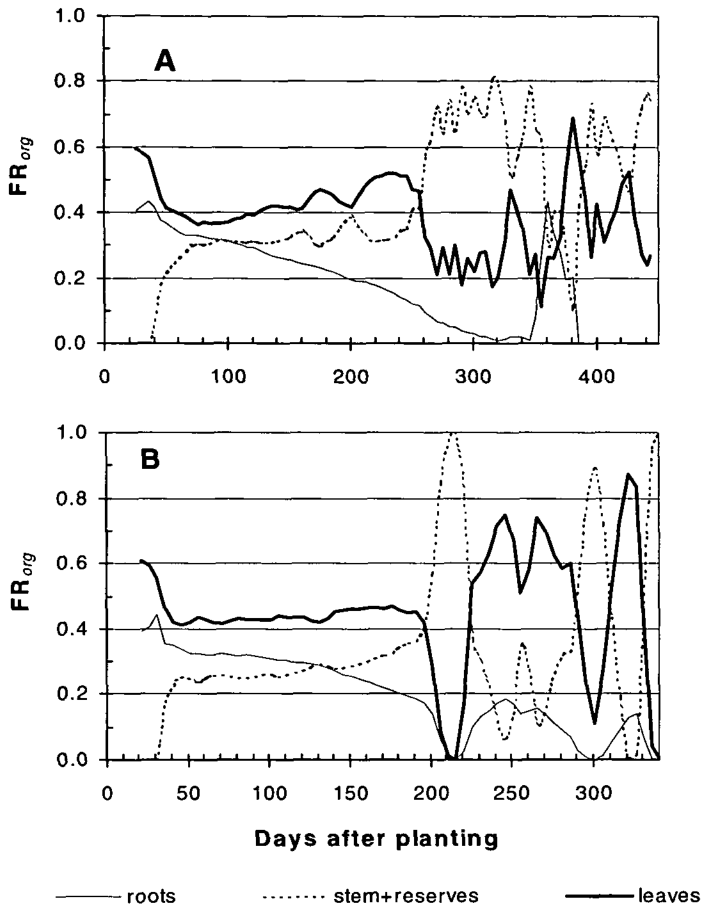


Figure 10.14 Partitioning fractions derived from the model results (water limited) for sugarcane (a) Piracicaba experiment; (b) Araras experiment

10.7 Discussion

It is recognised that the method proposed for assimilate partitioning is still incipient, and that comparisons with the experimental soybean and sugarcane data yield no conclusive evidence to its general applicability for different crops under different conditions. Nevertheless, the realistic model results obtained and the theoretical considerations presented in sections 10.2 and 10.3 indicate that this approach is an attractive alternative to rigid DVS-dependent partitioning.

The advantage of the approach seems especially manifest for sugarcane, which during its long growing season is exposed to strongly varying radiation, temperature and water availability. Total above ground biomass was very well described for both experiments. This was less so for leaf dynamics. For example, the strong response in leaf growth to improved conditions, suggested by the model for the Araras experiment between 220 and 250 d.a.p. (figure 10.13), is not confirmed by the field data. This seems to invalidate the hypothesis that rapid recovery of leaf area is possible thanks to adaptive changes in assimilate partitioning and remobilization of stored carbohydrates. On the other hand, Inman-Bamber (1991) reported a very quick and strong response of sugarcane leaf expansion to irrigation after dry spells and Inman-Bamber (1994) and Robertson et al. (1998) reported a strong correlation between leaf expansion and temperature of well watered sugarcane. The lack of response and very small observed LAI values of the present study could also be explained by e.g. nitrogen shortage. Note that the model results do reflect the differences leaf area in reported for the two experiments.

For soybeans, the model results (figure 10.9) suggest a good correspondence between simulation results and measured data, but some discrepancies appear during reproductive growth. These discrepancies are the integrated result of a number of factors which are not or only superficially addressed in the model, such as: sink size limitation during initial pod growth (Egli et al., 1981, Wilkerson et al., 1983), remobilization of carbohydrates from shells and their transformation to more complex compounds in the seed involving conversion loss (Pearen & Hume, 1981); nitrogen recycling; pod or seed abortion and soil-plant-air relations. Another problem with soybean simulation is that the model is very sensitive to the duration of the seed filling period. This was very well estimated for c.v. Davis, with the method based on the work of J.W. Jones et al. (1991). Siqueira & van den Berg (1991), using this method, found an average difference of 7 days between the calculated date of physiologic maturity and the actual harvest date for this cultivar. The derivation of parameter values for c.v.'s IAS5 and BR4 was entirely based on the present study. This is insufficient for an accurate estimation, because different varieties present different relations between development rate, photoperiod and temperature.

The foregoing suggests that the approach presented is able to describe the growth of soybean and sugarcane with acceptable accuracy but the paucity of well controlled experiments makes the determination of crop coefficients and model evaluation difficult. This can only be improved by analysis of more, well controlled experiments.

At first sight, the implementation of the priority rules proposed may seem excessively complex, even though the rationale is simple. The apparent complexity is related to the feedback between assimilate production, remobilization of reserves, assimilate partitioning and growth. This makes it impossible to consider these processes independently. On the other hand, accounting for this feedback cleared the way for a considerable reduction of the number of input parameters. For example, Boon-Prins et al., (1993) use at least 101 crop parameters for soybean, including 23 datapairs to describe partitioning, without considering stored reserves; the present model uses 58 crop parameters, 7 of which govern assimilate partitioning.

Several aspects that were not or only superficially addressed in the present study deserve attention for future investigation:

- The summary model with daily time steps considers assimilate reserves in stems only. Storage and remobilization of starch in leaves were ignored because this is principally a process of daily turnover (Chapin et al., 1990); but nitrogen recycling from old to young leaves or seed (which was also ignored) may play a significant role in reducing the cost of protein formation, especially during seedfilling (Wilkerson et al. 1983; but see also Penning de Vries et al., 1983, p. 45).

- A more sophisticated method may be necessary to describe root growth dynamics and root-shoot interactions.

- Several of the priority rules for assimilate allocation have a triggering effect and responses to stress and stress alleviation in the model all occur within one day time intervals (Δt). This causes strong fluctuation of the calculated partitioning fractions. It may be necessary to introduce more gradual transitions or delay factors, for example to simulate recovering from severe water stress.

- It may be necessary to consider sink capacity limitations during initial leaf expansion and initial seed filling, and sink demand limited assimilation in a closed canopy before the seed filling stage (Shibles et al., 1989, Goudriaan & van Laar, 1994).

- Partially related to the foregoing is the change in specific leaf area, its relation to temperature, light and water availability; and its effects on light use efficiency (Penning de Vries et al., 1989; Bunce, 1990; Witkowski & Lamont, 1991; Rundell, 1991).

Future studies might elucidate if these issues can be incorporated in summary models with a "smart crop" perspective, and if the improvements obtained outweigh the additional model complexity and data needs.

The method used to describe aeration stress seems adequate, but it is questionable if the same parameter values would hold for different soils. An accurate description of transient aeration stress in crops with adaptive mechanisms may be too complex for summary crop models. The approach of this study helps the user to identify situations where aeration stress may affect crop growth, but should not pretend to provide an accurate description.

10.8 Conclusions

1. There is overwhelming evidence that assimilate partitioning in plants (including field crops) is to a great extent governed by adaptive responses. It is necessary and possible to take this into account in summary crop growth models.

2. The "smart crop" approach of the present study is an attractive alternative to the rigid partitioning functions of most other "universal" crop growth models.

3. Further studies are necessary to evaluate the approach proposed, to identify crop parameter values, and to find out if refinements are necessary and possible with respect to factors such as sink limitation, response delay, nitrogen recycling, root dynamics and root-shoot interactions, without disturbing the balance between practical applicability and data requirements.

11. APPLICATION OF A SUMMARY CROP GROWTH MODEL FOR QUANTIFIED LAND EVALUATION

11.1 Introduction

Yield potential is a key indicator in quantified land evaluation because it represents the biophysical ceiling of performance of specific land-use systems at the present insights. Knowledge of crop yield potentials can help to identify those areas where introduction of a new crop (or agriculture as such) is most likely to be successful. Analysing the gap between the (theoretical) yield potential and observed yields in cropped lands can help to identify areas where management might be improved. This is of special relevance for Brazil, where large areas are still under natural vegetation, which according to many should be explored for agriculture; whereas others are of the opinion that most of these natural areas must be preserved, maintaining that more intensive use of existing agricultural lands would be more than sufficient to satisfy future needs for labour opportunities and agricultural products.

As mentioned in chapter 1, yield potentials can be calculated with empirical methods as well as with dynamic systems analysis. The latter approach is based on physical, chemical and biological laws, rather than on statistical correlation. It has been claimed that therefore, models based on dynamic systems analysis have wider application. For regional studies in developing countries, simplified so-called summary models seem to be most appropriate (Dumanski and Onofrei, 1989; Rabbinge & van Latesteijn, 1992; Rötter, 1993; Driessen, 1997).

The previous chapters have shown however, that there are many uncertainties related to the accuracy with which biophysical processes are modelled. To check all these uncertainties, many detailed experiments would be necessary under well-controlled conditions to test algorithms, to identify the most appropriate level of refinement, to identify crop parameter values for selected species and cultivars and to compare model results with reliable field data. This is expensive and takes many years of research.

In the study regions of this thesis there are many medium and large farms (200 to several thousands of ha) with fairly uniform management at a high level. Some farmers have kept records of management and crop yields for several years. The production situation on these farms may well be fairly close to the attainable under water limitation, i.e. small limitations due to nutrient insufficiency and minor losses due to yield reducing factors. Hence, management and yield records could be used to get a first impression of the usefulness of a summary crop growth model for the calculation of production potentials. A good correspondence suggests that the model is a valuable tool, whereas a poor correspondence means that (1) the model or its parameter values are weak, and/or (2) input data are inaccurate, and/or (3) yield limiting and/or reducing factors have an overriding impact on actual yields. In these cases the model, as it is, would be of little immediate relevance to the assessment of production situations at the examined level, and additional research would be required to identify the reasons for discrepancies.

A more comprehensive impression of model performance can be obtained by considering several data sets. In our case, the adapted PS123 summary crop growth model presented in chapter 10, was roughly calibrated against sugarcane growth data from the surroundings of Araras and soybean data from the Passo Fundo region. Comparing model results with yield records obtained in these areas and in the other study region (Assis), would reveal if the model and input parameters could be applied to new areas without much calibration.

The objective of this chapter is to check how water-limited biophysical yield potentials (sometimes referred to as attainable yields) calculated with the model presented in chapter 10, compare with actual yield records of commercially grown sugarcane and soybean in the study regions, and to explore the reasons for possible discrepancies.

11.2 Materials and methods

11.2.1 On-farm yield records

Soybean yield records from the study fields of the Passo Fundo and Assis regions were provided by the farmers. Only data referring to c.v.'s Davis, BR-4 and IAS-5 were considered. For Passo Fundo, records on 25 crops were complete with date of planting and harvest. For Assis, 21 complete yield records were available. The yield data, from harvests between 1983 and 1989 refer to seed weights, determined just before storage, with moisture content of 14%. No regional c.v. specific data are available on the seed/pod ratio at harvest. The average values for the experiments reported in chapter 10, were 0.76 for c.v. Davis and BR-4, and 0.77 for c.v. IAS-5.

The Usina São João sugarcane mill provided data on planting, harvesting and fresh cane yields of 81 sugarcane crops on the 15 Araras study fields (locally called *zonas*), each comprising 2-5 adjacent plots (called *talhões*) with identical management. Data on cane composition at harvest (contents of sugar and insoluble solids in fresh cane stalks) were available for 51 of these crops. These data pertain to samples taken randomly from lorries entering the mill after harvest. For Assis, planting and harvesting dates and fresh cane yield data for 55 sugarcane crops on 11 fields were supplied by Usina Nova América and Cia. Agrícola Capivari. Data on cane composition were available in 45 cases. In both regions, the yield data cover several years between 1979 and 1988. All cane yield records refer to c.v. NA-5679, which was the most common cultivar in the study regions at the time of field research. Cane dry matter yields ($kg\,ha^{-1}$) were calculated as the product of fresh cane yield and contents of sugar+insoluble solids. In those cases where only records on fresh cane yield were available (30 cases in Araras, 10 in Assis), dry matter yields were approximated by assuming the average dry matter (sugar+insoluble solids) content of fresh cane stalks at harvest: 0.29 $kg\,kg^{-1}$.

11.2.2 Calculated yield potentials

The crop growth model used to calculate water-limited biophysical yield potentials, is the modified version of PS123 (Driessen and Konijn, 1992; Driessen, 1996) presented in chapter 10.

The crop parameter values used are as detailed in tables 10.2 (soybean) and 10.3 (sugarcane). Recall that these values were partly derived from published literature and partly by calibration of the model against the experiments discussed in chapter 10.

Calculated soybean pod yield potentials were roughly transformed to harvestable seed yield potentials by multiplication by the average seed/pod ratio of the experiment of chapter 10 (i.e. 0.76) and division by 0.86, i.e. 1.0-0.14, where 0.14 is the standard seed moisture content ($kg\,kg^{-1}$) at harvest.

For ratoon sugarcane, the rooting depth at emergence was set to the maximum rooting depth (RDM), i.e. it is assumed that the root system is still intact immediately after harvest (c.f. Ball-Coelho et al., 1992). Initial biomass values were set to 100 $kg\,ha^{-1}$ carbohydrate reserve equivalents for soybean and 660 $kg\,ha^{-1}$ (=2/3 * 1000) for plant sugarcane. For ratoon cane, this value was added to the final root biomass of the preceding harvest.

11.2.3 Weather data

Weather data were provided by official meteorological stations situated within 50 km from the farmers' fields. Measured daily precipitation and minimum and maximum temperature data were used; daily values for air humidity, wind speed and hours of sunshine were derived from monthly values.

11.2.4 Soil data

In Araras, on 13 fields, one soil profile was examined in detail, as described in chapter 5. These profiles were used as reference profiles for the field in which they were sited. For the 2 fields without profiles, data were used from profiles of other fields with similar soil texture and chemical properties of the auger samples (see chapter 4 and 5). The same procedure was followed for the sugarcane fields of Assis (11 fields, 6 with profile). All soybean fields in Passo Fundo (6 fields) and Assis (5 fields) were represented by a soil profile. Soil data used for input to the model are the water retention curve (the one for the 45cm depth was used to represent the entire soil) and the soil water potential at "field capacity", which was set to the tensiometer reading two days after field saturation (ψ_{2d}), as explained in chapter 6.

Maximum rootable soil depths (RDM) could not be obtained directly by examining the soil profiles. Except some of the soybean soils with clear evidence of compaction, the soils studied do not present any physical constraint to root growth.

However, many of them contain toxic levels of aluminium that may form a chemical barrier below the limed plough layer (Furlani et al., 1991; Foy, 1992). More soluble (and more expensive) gypsum could be used to mitigate the effects of subsoil acidity (Ritchey & Sousa, 1997) but this is not done in the study regions because returns on investments are difficult to assess. Root distribution recorded in the soil profile descriptions is not of much help to identify RDM of the soils studied because, when the soils were examined, crops on different soils were in different stages of development. Besides, it is difficult to quantify the implications of such general statements as "few fine roots". Critical, c.v. dependent, levels of Al^{3+} may fairly well be established in nutrient solutions, but do not apply to field situations (Keltjens, 1997). As a rule of thumb, a level of 50-60% Al^{3+} saturation (exchangeable Al^{3+} in relation to ECEC) is often used to identify toxic layers. Jones et al. (1991) proposed a stress factor for root growth in relation to Al^{3+} saturation with 2 critical values, one at which root growth is first affected by Al toxicity; the other at which root growth is completely inhibited. An analogous - but not less arbitrary - method was used for this study to calculate an "effective rootable depth" as a function of the Al^{3+} saturation of each soil horizon within the maximum rooting depth: For the reference profiles, it is assumed that the relative rootability of a soil horizon is 1.0 if Al^{3+} saturation is less than 40 %, and 0.0 if Al^{3+} saturation exceeds 80 %. An intermediate value is taken when Al^{3+} saturation is between 40 and 80 %. The rootability values of the soil horizons are multiplied by the horizon thickness (down to a depth of 200 cm) and summed to obtain the value of the effective rootable depth.

Initial soil water content was set to θ_{2d} (see chapter 6) for soybean and plant cane, and to the final value of the preceding harvest for ratoon cane.

11.3 Results

11.3.1 Soybean

Preliminary runs of the model indicated that several of the Passo Fundo crops should have failed completely due to aeration stress, whereas in reality they produced good yields. This did not occur for the Assis region, where the soils have less compaction problems.

Apparently more realistic results were obtained by simply ignoring the possibility of aeration stress. The results are presented in figure 11.1, which compares observed soybean yields with calculated yield potentials. Calculated yield potentials tend to be considerably larger than actual yields and yield gaps tend to increase with increasing calculated yield potential. The average difference is 1200 kg ha^{-1} in Passo Fundo and 1975 kg ha^{-1} in Assis. Recorded yields are on the average 66 % of calculated yield potentials in Passo Fundo and 57% in Assis. Interestingly, calculated yield potentials are clearly correlated with recorded yields in Passo Fundo ($R^2 = 0.30$), but not at all in Assis.

Figure 11.2 presents the relation between calculated and observed lengths of growing period (LGP, days), i.e. the duration between sowing and harvesting dates vs. the calculated period between sowing and harvest maturity (R8) as defined by Fehr et al.,

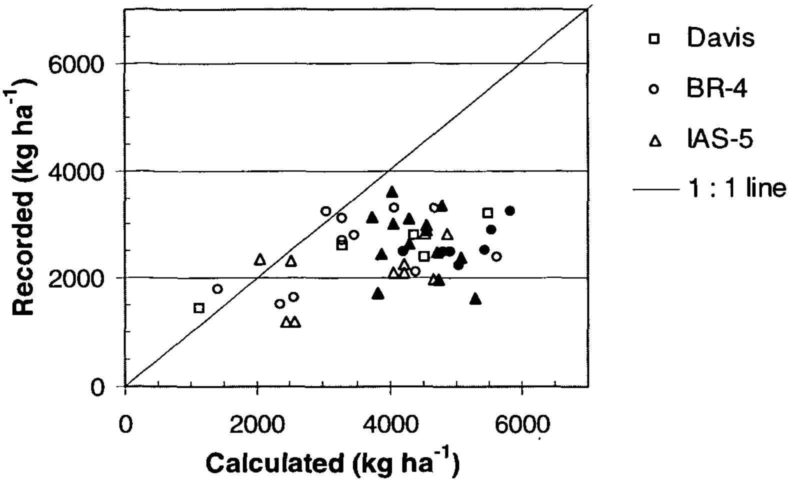


Figure 11.1 Comparison between recorded soybean yields and yield potentials calculated without considering soil aeration. Open symbols Passo Fundo; solid symbols: Assis.

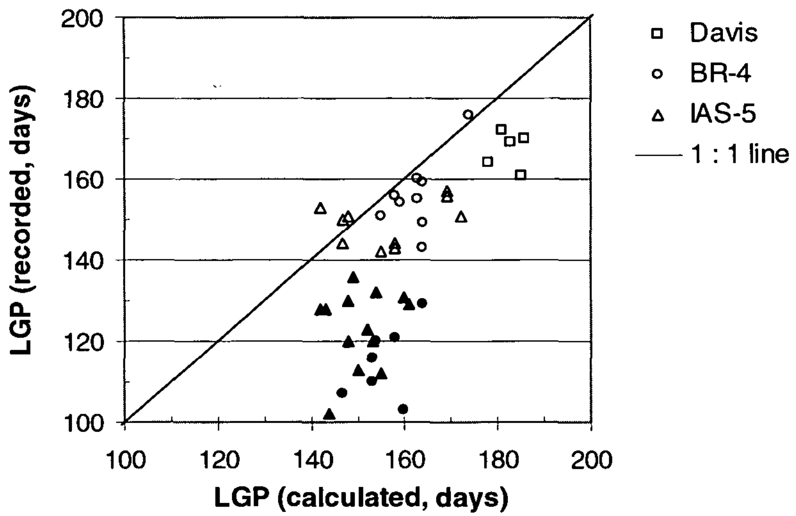


Figure 11.2 Comparison between observed and calculated lengths of growing periods (no. days between sowing and harvest). Open symbols Passo Fundo; solid symbols: Assis.

(1971). The yield potentials calculated for Passo Fundo correspond fairly well with the recorded values but they tend to overestimate LGP, when it is long. Figure 11.3, which presents LGP as a function of planting date, shows that these discrepancies occur principally when planting is early in the season. For Assis, the model tends to strongly overestimate LGP (figure 11.2) and simulated data are not correlated with the observed ones, but the shape of the trend over the year (figure 11.3) seems to be more or less correctly described.

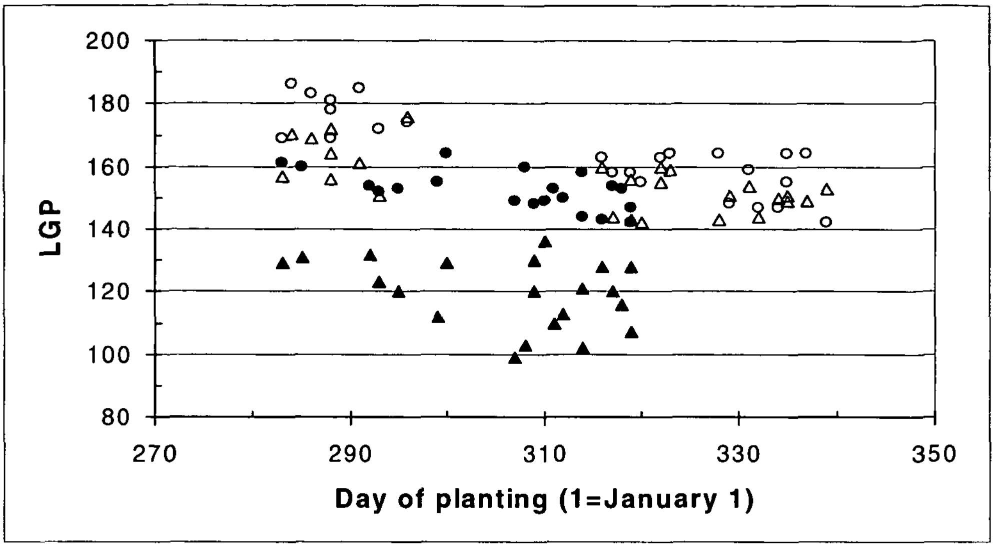


Figure 11.3 Observed and calculated lengths of growing periods (LGP, days) in relation to day of planting. Open symbols: Passo Fundo; closed symbols: Assis. Triangles: recorded values; circles: calculated values

Figure 11.4 compares recorded soybean yields with calculated yield potentials after averaging by field (figure 11.4a) and by year (figure 11.4b). The results of figure 11.4a suggests that differences in yield potential between fields as calculated by the model are not reflected in actual yield records. Recorded and simulated years with lowest and highest yields correspond well in the Passo Fundo (1985 and 1987), but not in Assis (figure 11.4b).

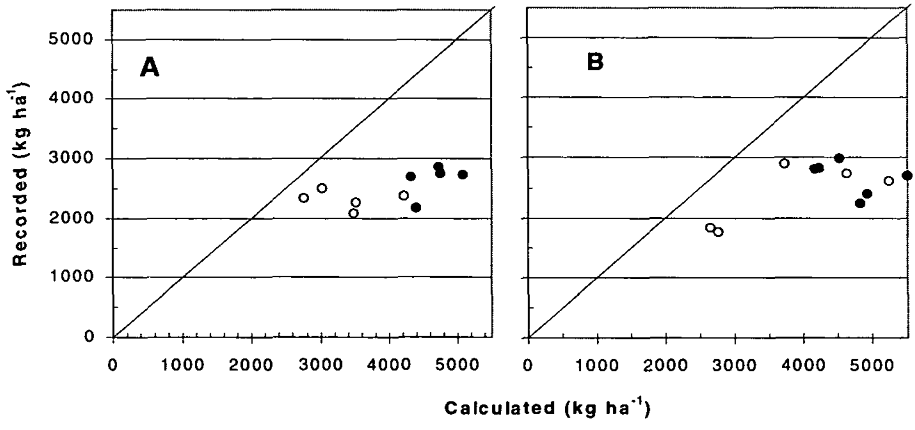


Figure 11.4 Comparison between observed soybean yields and calculated yield potentials. A. averaged by field; B. averaged by year. Open symbols: Passo Fundo; closed symbols: Assis

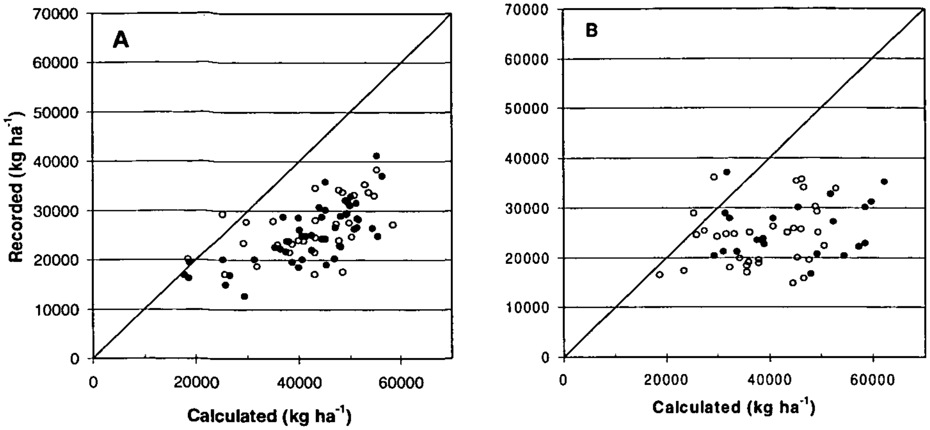


Figure 11.5 Comparison between recorded sugarcane yields and calculated yield potentials. A: Araras, B: Assis. Open symbols model results suggest no flowering; solid symbols: model results suggest flowering

11.3.2 Sugarcane

Observed and calculated sugarcane yields (dry stem masses) are compared in Figure 11.5. Calculated yield potentials are generally considerably larger than recorded cane yields, and yield gaps tend to increase with increasing yield potentials. The average difference between simulated yield potentials and harvested dry cane yields amounts to some 16500 kg ha^{-1} for both study regions; and actual yields are on the average 61% of calculated yield potentials. Interestingly, calculated yield potentials are fairly well correlated with recorded cane yields in Araras (R^2=0.43), but very weakly in Assis (R^2=0.07). Sugarcane crops that may have been subject to flowering, as assessed by the method explained in section 10.6.1, are indicated in figure 11.5 by solid symbols. They are apparently randomly distributed over the graphs without affecting the relation between recorded yields and calculated yield potentials. Application of different methods to assess flowering (not shown) based on Pereira et al. (1983) resulted in basically the same pattern.

Note that part of the difference between the 1:1 line and the trend line in figure 11.5 is due to harvest losses and cane tips and basal parts which are included in the modelled yield potentials but not in the yield records. No quantified data are available for these loss factors, but they are probably of minor importance, because harvesting is done very carefully, manually, and basal parts and cane tips are small compared to the cane stalks of 3 m length or more. Their effect on scatter in Figure 11.5 is probably even smaller.

Figure 11.6 compares recorded and calculated sugarcane yield potentials after averaging by field (figure 11.6a) and by year (figure 11.6b). The results of figure 11.6a suggest that for Araras, the model discriminates fairly well between fields with low and high yield potentials, and even better between high yielding years and low yielding years; but not for Assis.

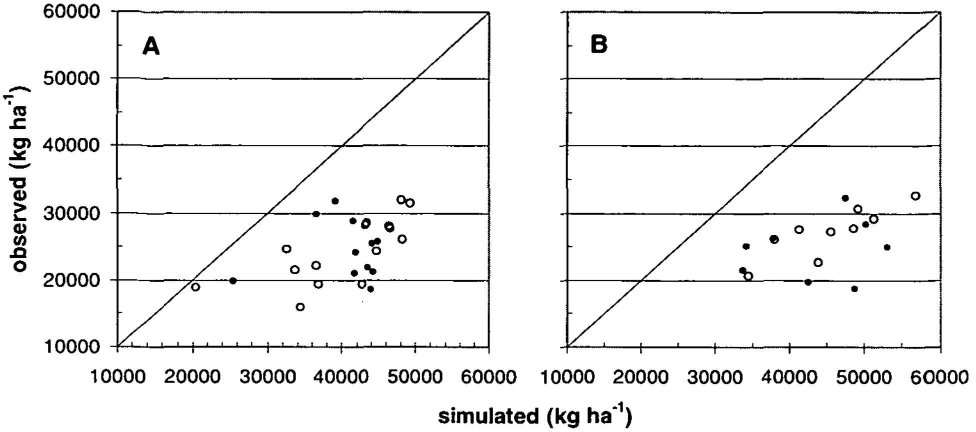


Figure 11.6 Comparison of simulated yield potentials and recorded yields of sugarcane stems (dry matter). A. Averaged by field; B. Averaged by year. Open symbols: Araras; solid symbols: Assis

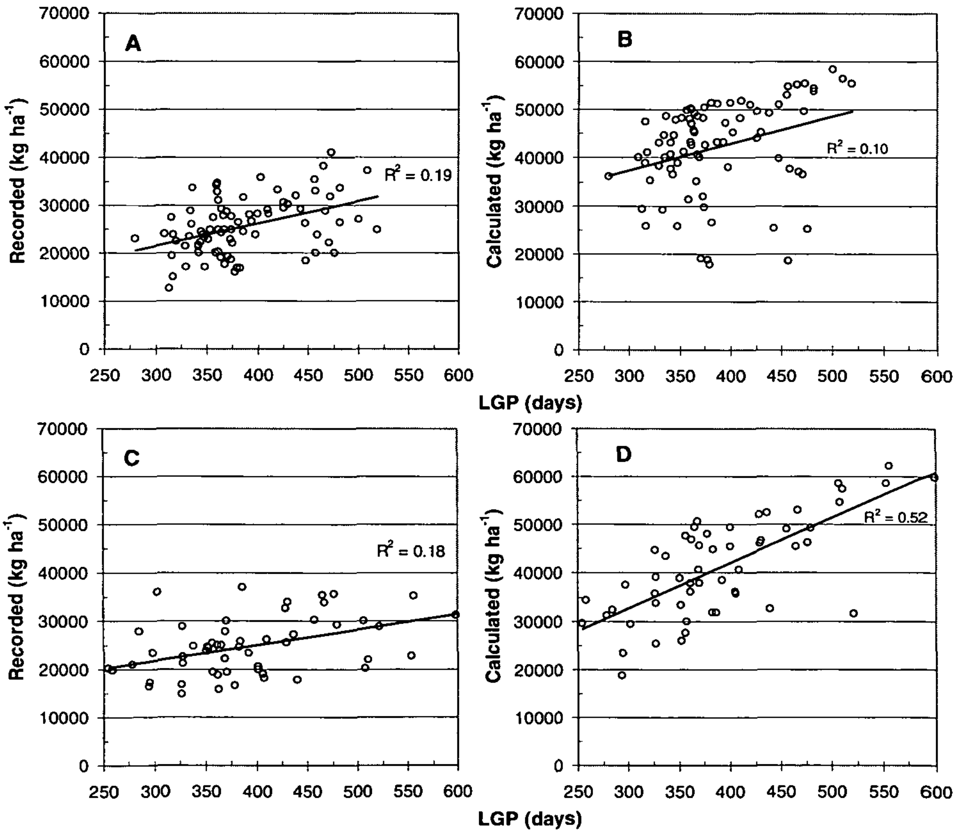


Figure 11.7 Sugarcane yields in relation to LGP. A Araras, recorded; B Araras, calculated; C Assis, recorded; D Assis, calculated. Lines: regression lines

One of the main reasons for high yields of sugarcane in comparison to other crops is the long growing period (Irvine, 1983) but sugarcane yields (recorded and calculated) were rather poorly correlated to LGP (i.e. duration between planting and harvest or between consecutive ratoons), especially in Araras. This is shown in figure 11.7. Even so, for Assis, the single variable LGP is better correlated to cane yield than the results of the crop growth model. Interestingly, figure 11.8 shows that the Araras yield records are more strongly correlated to the initial date (i.e. date of planting or previous ratoon) than to LGP. This phenomenon is expressed in both the simulated and the observed data. Simulated cane yields for Assis are strongly correlated to the initial date, but the observed yields do not present any significant correlation.

11.4 Discussion

The relations between simulated and actual yields as presented in figures 11.1 for soybeans and 11.5 for sugarcane could be interpreted as follows.

Simulated yield potentials tend to be considerably greater than actual yields, because actual yields are conditioned by limitations due to nutrient stress and yield reductions caused by plagues, diseases, harvest losses etc. which are not considered by the model. The yield gap tends to disappear when simulated yields are small because crop yields are principally conditioned by the most limiting factor which in these cases would be water, light and/or temperature (considered by the model). The scatter in the relations could be the result of accidental events (e.g. plagues, hailstorms) and interactions, e.g. between nutrient availability and water sufficiency.

The results for soybeans in Passo Fundo show that calculated LGP's correlate well with the recorded ones (figures 11.2 and 11.3), which however tend to be overestimated. The overestimation may largely be related to the fact that, in dependence of (expected) weather conditions, farmers often harvest soon after physiologic maturity (stage R7 of Fehr et al., 1971), i.e. some 2 weeks before harvest maturity (stage R8) as calculated by the model (Siqueira & van den Berg, 1991).

Model results fairly well describe year to year variations in sugarcane yields for Araras and soybean yields for Passo Fundo after averaging, but differences between fields are not so well expressed, especially for soybean. These results suggest that farm management in the study regions aims at target yields of 2500 - 3000 kg ha^{-1} for soybean and 25000 - 30000 kg ha^{-1} (dry cane) for sugarcane, corresponding with expected yields mentioned in Brazilian fertilizer manuals (e.g. IAC, 1987). Calculated yield potentials suggest that, in favourable years, yields of some fields could be doubled if sufficient nutrients are supplied and yield reducing factors controlled. If this would be economically viable is beyond the scope of this thesis.

The interpretations given above may be roughly correct, but it must be realised that calculated yield potentials contain considerable uncertainties, because: (1) the model is a rough simplification of reality; (2) many crop coefficients listed in tables 10.2 and 10.3 were chosen rather arbitrarily; and (3) reference soil profiles, weather data and derived variables

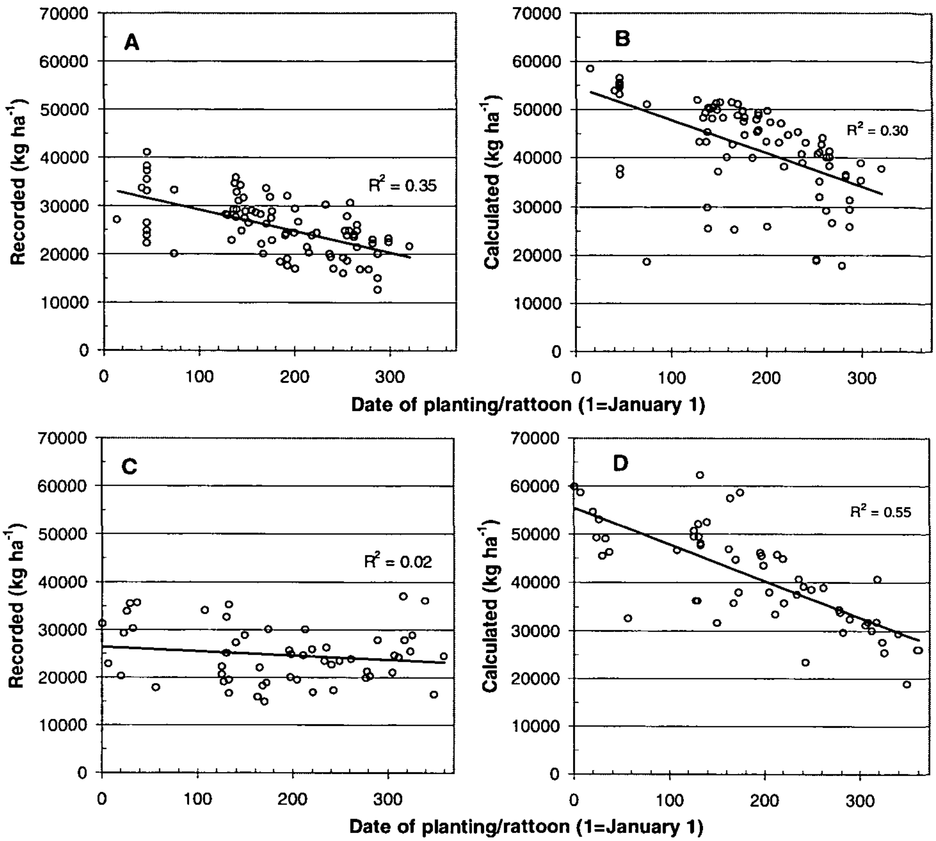


Figure 11.8 Sugarcane yields in relation to date of planting or ratoon. A Araras, recorded; B Araras, calculated; C Assis, recorded; D Assis, calculated. Lines: regression lines

may be much less representative than assumed. These factors may contribute to scatter, masking the true yield potentials and yield gaps, or cause systematic errors in calculated yield potentials (Nonhebel, 1993). Some of the results of this study help to illustrate the impact of some error- or uncertainty-factors. The consequences of errors and/or uncertainties related to water availability aspects will be quantitatively addressed in chapter 12.

The most striking discrepancy between model results and harvest records are the poor estimates of LGP for soybeans in Assis. The differences of up to 58 days for Assis cannot be explained by premature harvesting. They rather seem to be due to the approach used to describe the phenological development of soybean, which was mainly based on experimental data obtained in Quincy, Florida (USA), at 30°N (Jones et al., 1991). Photoperiod and temperature at this location are quite comparable to Passo Fundo (28°15'S), but deviate considerably from the conditions in Assis (23°S). Inaccurate timing of key phenological development stages obviously results in inaccurate yield potential estimates. For example, when the simulated date of onset of reproductive growth is incorrect, the modelled soybean crop will experience different weather conditions during the seed filling period than the real crop with which it is compared. This discrepancy may largely explain the poor correlation between modelled and recorded yields in Assis.

Another point of concern is the strong impact of aeration stress on the modelled soybean yields of the Passo Fundo region. This seems to confirm the feeling expressed in chapter 10, that aeration stress is very difficult to describe quantitatively. These difficulties are related to adaptive responses, and the strongly simplified description of the relation aeration vs. transpiration vs. photosynthesis (Appendix 2). This algorithm is more sensitive to errors than the one for drought stress (see introduction of chapter 9) because of the lack of a corrective feedback mechanism: when soil aeration at day i is underestimated, water uptake by roots will also be underestimated, and aeration at day i+1 will again be underestimated etc. Hence relatively small errors in the estimate of soil air content or in its modelled effect on water uptake may result in large errors in the calculated consequences. Note also, that data from the 45 cm soil layer were used to represent entire soil profiles.

The average ratios between actual yields and calculated water-limited yield potentials, compare well with the median values of 60-70% for several crops in the European Communities reported by De Koning & van Diepen (1992). However, if the calculated maximum soybean yield potentials are practically attainable in the study regions is questionable. Soybean yields of 3000 kg ha^{-1} are internationally regarded as good and yields of 4000 kg ha^{-1} as very high; yields exceeding 6000 kg ha^{-1} have been reported exceptionally (Whigham & Minor, 1978; Whigham, 1983).

Irvine (1983) reported sugarcane yields of more than 60000 kg ha^{-1} on commercial fields in Colombia and Iran. However, results of Robertson et al. (1996) in Queensland (Australia) suggest a yield plateau at some 50000 kg ha^{-1}, which they attributed to the loss of live millable stalks associated with lodging causing smothering and stalk breakage followed by the attack by pathogens and rats.

The Araras and Assis data on calculated and observed sugarcane yields show quite different structures. Comparing calculated crop yield potentials with yield records suggest that adapting sugarcane management to higher target yields would be especially rewarding in Assis, which seems to present a small risk of unfavourable (weather) conditions. This could explain the lack of correlation between calculated yield potentials and recorded harvested yields in Assis. It seems plausible however, that the lack of correlation is related to errors in the model or in crop coefficients. Some of the crop coefficients, which were determined by calibration for the experiments near Araras (chapter 10), may not apply to Assis; or errors in some coefficients may have greater impact on the results for Assis than for Araras. For example cold spells occur more frequently in Assis than in Araras, even though the average winter temperature is higher in Assis. A wrong relation or correction factor to modify crop growth in times of suboptimal temperatures may thus cause greater overestimates in the results for Assis than for Araras.

In contrast to expectations, calculated sugarcane yield potentials (Araras) and recorded yields (Araras and Assis) are rather poorly correlated to LGP (figure 11.7). Figure 11.8 indicates a stronger relation between yield and date of planting or ratoon for calculated yield potentials in Araras and Assis and for recorded yields in Araras, but not in Assis. Personal communications and literature search suggest that these trends have not been detected before. A possible explanation for the trends in Araras is that, even though growth rates between April and October are very slow, early planting or ratoon gives the cane crop the opportunity to develop a closed canopy until the beginning of the hot rainy season, which starts in November. Then the crop can take full advantage of the favourable conditions of light and water availability from November until March. Longer growing periods in Araras imply that the cane crops remain longer in the field during the dry and relatively cold season (May to September) with little effect on yield. These trends are well illustrated by the growth experiments of figures 10.12 and 10.13. In Assis, with somewhat higher average winter temperature and rainfall, a longer growing period may have more beneficial effect than in Araras, but the potential advantage of early planting or ratoon may be largely counteracted by a greater risk of adverse conditions during canopy establishment.

A problem of special relevance to sugarcane is that flowering and its effects on cane yield are difficult to predict. Nevertheless, there are several reasons why calculated sugarcane yield potentials of this study should correlate better with true yield potentials than calculated soybean yield potentials:

- All sugarcane fields were well drained;
- the ratio seed/pods at harvest of soybeans is not a constant; observed data pertain to harvested seed and calculated data referring to pods were roughly transformed to seed yield potentials;
- the physiological characteristics of sugarcane change very little between emergence and harvest (in most cases there is no reproductive growth);
- planting and harvest dates of sugarcane are specified, and simulation stops when the harvest date is reached. The simulated soybean crop is harvested at the date of maturation calculated by the model.

11.5 Conclusions

1. Comparison between calculated and actual yields for Passo Fundo (soybean) and Araras (sugarcane) reveals plausible relations. However, possible errors in the model, parameter values and input data may have masked true yield gaps or introduced systematic errors in calculated crop yield potentials.

2. Crop growth models using parameter values based on rough calibration in one region should not be applied for practical use in new regions without additional field

experimentation, at the risk of producing strongly biased yield potential estimates and suggesting non-existing trends.

12. UNCERTAINTIES IN THE APPRAISAL OF WATER AVAILABILITY AND CONSEQUENCES FOR SIMULATED SUGARCANE YIELD POTENTIALS

12.1 Introduction

Most crop yield potentials calculated in chapter 11 are considerably higher than actual on-farm yields. This is a common phenomenon. Ideally, these "yield gaps", between calculated yield potentials and actual yields, would represent the effects of management practices that eliminate specific yield limiting and reducing factors (e.g. nutrient shortage, weeds, pests and diseases), *viz.* those factors that are not considered by the model (Boote et al., 1996, Van Diepen et al., 1998). However, there are additional reasons for differences between calculated yield potentials and actual yields. Two basic types of sources of discrepancies have been indicated in previous chapters: (1) inadequate input data and/or transfer functions to generate these data and (2) errors or oversimplifications in the model. A third category, errors/uncertainties in the actual yield data, may be of special importance when model results are compared with on-farm yields. These three factors cause scatter, blurring the relations between yield potentials and actual yields, or cause biased yield gap estimates. This is particularly disturbing in analysis in countries such as Brazil, where basic data are scarce and data sets for calibration and validation are virtually absent. Quantified indications of the impact of different types of error on model outcomes are needed to guide further research, to identify priorities in data collection, and to judge the appropriateness of specific types of models for specific purposes such as explanation, exploration, or prediction.

This chapter looks into errors/uncertainties in actual sugarcane yield records and explores uncertainties in the appraisal of the water balance and their consequences for calculated sugarcane yield potentials. The following reasons for possibly erratic model results are addressed:

1) Data on soil-water relations were obtained from reference profiles, whereas chapters 4 and 5 show that the soils are quite heterogeneous with respect to some important chemical and physical properties. Chapters 6 and 7 show that transfer functions to predict soil-water relations from stable soil properties such as soil texture produce rather poor estimates of $\theta_{2d\text{-}1.5MPa}$ as a representation of available water capacity.

2) The method used to model crop water uptake/transpiration is strongly simplified and somewhat speculative (chapters 8 and 9).

3) Maximum effective rootable soil depth (RDM, cm) was estimated in chapter 11, as a function of Al^{3+} saturation observed on the reference profiles.

Interestingly, the first two items listed are typically the domain of soil physicists and hydrologists. Research on Brazilian strongly weathered soils on these items has been mainly directed towards detailed water balance studies (De Jong van Lier & Libardi, 1997, Dourado-Neto et al., 1999, Carlesso & Santos, 1999) and the establishment of pedotransfer functions (Arruda et al., 1987; Tomasella & Hodnett, 1998). The third item is generally considered the domain of soil fertility specialists. They recognise that restricted rooting on soils with high Al^{3+} levels affects water availability (Furlani et al., 1991; Resende et al., 1996a,b), but research has mainly addressed physiological mechanisms, the breeding of Al-tolerant cultivars and the correlation of lime (or gypsum) gifts against final crop yields (Ritchey & Sousa, 1997; Caires et al., 1999). Little research attention has been given so far to the interactions between atmospheric conditions and soil physical and chemical properties in relation to water availability and their consequences for crop yield.

The objectives of this chapter are (1) to assess the impacts of the above mentioned errors/uncertainties on calculated sugarcane yield potentials of the Araras region in relation to the inferred yield gaps and (2) to demonstrate that uncertainty propagation analyses should be a standard practice in quantified land use systems analysis.

Results of the assessment must be interpreted with reference to the situation studied and the crop model. Uncertainties that strongly affect results certainly need consideration: more or better basic data are required or the model needs improvement, or both. Uncertainties that contribute little to the variation of calculated results suggest little need for better data, but the possibility that one or more factors are not well accounted for in the model should not be excluded. For example, a model that does not take due account of chemical root barriers may also incorrectly reflect the effect of uncertainties in other soil properties on crop yield. In such cases, poor results are obtained with apparently low levels of uncertainty. The study indicates a minimum level of uncertainty because only a part of all possible errors is considered.

12.2 Methods

12.2.1 Research strategy

- Data from the Araras region (figure 3.2) were used for this study: 81 crops of sugarcane (cv. NA5679) on 15 fields (±100 ha each), with each field comprising 2-5 adjacent plots. Soil data had been obtained from auger samples at 7 to 16 sites in each field and, in most fields, from one reference soil profile. See chapters 5 and 6 for sampling methods and analytical methods; profile descriptions are available from the author, on request.

- Yield variation between adjacent plots within fields was determined to assess uncertainty in actual yield data.

- Probability density functions were determined for the maximum rooting depth (RDM) in dependence of Al saturation, and for the volume fraction of soil water held at potential > -1.5 MPa, 2 days after field saturation ($\theta_{2d\text{-}1.5MPa}$, $cm^3\ cm^{-3}$; often referred to as available water capacity). These functions were used in a Monte Carlo procedure, generating realisations of RDM and/or $\theta_{2d\text{-}1.5MPa}$ for input in the crop growth model presented in chapter 10. This model was used to calculate water limited sugarcane yield potentials (chapter 11) using soil data inferred from the reference profiles.

- Comparative crop growth calculations were done with two alternative mechanisms of soil water uptake by the crop. Method 1 assumes that water uptake is determined by the part of the soil in which water is most readily available. Method 2 assumes that water uptake is a function of the total amount of available soil water. Method 2 is commonly applied by irrigation engineers, but method 1 seems more appropriate in dry land cropping, particularly if dry spells precede rains that are insufficient to wet the entire root zone. Theoretical considerations are given in chapters 8 and 9; algorithms used are in Appendix 2. Both options use the method of Allen et al. (1998) to calculate soil water depletion fractions (p_{soil}).

- Estimation errors in actual yields were compared with yield potentials calculated with average values for $\theta_{2d\text{-}1.5MPa}$ and/or RDM and with stochastically generated data founded on the two alternative mechanisms of water uptake by the crop. This procedure is used to assess the importance of each (type of) error/uncertainty in relation to the gaps between calculated yield potential and actual yield, provided that point data are used to calculate the yield potential of a single harvest on a single plot.

12.2.2 Assessment of uncertainties in actual yield estimates

Cane dry matter yields (kg.ha^{-1}) are calculated (chapter 11) as the product of fresh cane yield and content of sugar+insoluble solids. For the present study, standard deviations of yields from individual plots within a field were estimated as well. If only data on fresh cane weights were available (30 cases), average dry matter yields (Y_k) and standard deviations of yields from adjacent plots for each harvest (S_{yk}) were estimated as:

$$Y_k = (\Sigma_{i=1,n} C.F_{i,k}.A_i)/(\Sigma_{i=1,n} A_i) \quad (1a)$$

$$S_{Yk}^2 = C^2.S_{Fk}^2 + F_k^2.S_C^2 + 2Y_k.S_C.S_{Fk}.r_{C,F} \quad (1b)$$

where

Y_k is estimated dry cane yield (kg ha^{-1}) of a field at harvest k;

C is average dry matter (sugar+insoluble solids) content of fresh cane stalks at harvest (= 0.29 kg kg^{-1});

n is the number of plots in the field;

$F_{i,k}$ is mass of fresh cane stalks at plot i at harvest k (kg ha^{-1});

A_i is the surface area of plot i (ha)

S_{Yk} is estimated standard deviation of dry cane yields among plots within a field at harvest k (kg ha^{-1});

S_{Fk} is standard deviation of fresh cane yields among plots within the field at harvest k (kg ha^{-1});

S_C is estimated standard deviation of dry matter content of fresh cane, calculated from data provided by the mill (= 0.029 kg kg^{-1});

$r_{C,F}$ is the correlation coefficient of fresh cane yield and cane dry matter content (= -0.491).

Note that this assessment only considers random variation and not systematic differences caused by e.g. harvest losses and cane tips and basal parts that remain on the field.

12.2.3 Generating rooting depths with the Monte Carlo method

The probability density functions for RDM, from which random drawings were used as input in the simulation model, were constructed as follows.

In chapter 11 it was assumed that the rootability of a soil horizon is unaffected (i.e. "1.0") if Al^{3+} saturation is less than 40 % and rootability is "0.0" if Al^{3+} saturation exceeds 80 %. An intermediate value was taken by linear interpolation if Al^{3+} saturation is between 40 and 80 %. The rootability indices of each soil horizon were multiplied by the horizon thickness (down to a depth of 200 cm) and summed to obtain a value of the "effective" RDM. This approach requires that Al^{3+} saturation data be for every soil horizon, whereas Al^{3+} saturation is normally determined only on auger samples of the 0-20 cm and 60-80 cm layers. Figure 12.1 plots the calculated "effective" RDM against Al^{3+} saturation of the 60-80 cm layer ($Al_{60\text{-}80}$) for all 31 soil profiles that were analysed. Thirteen of these are from the Araras region. Al^{3+} saturation of the 0-20 cm layer ($Al_{0\text{-}20}$), being modified by liming, never exceeded the lower threshold value of 40%. The following “pedo-transfer function” was derived from the available data to estimate RDM from $Al_{60\text{-}80}$:

$$RDM_{i,j} = a\, Al_{j,60\text{-}80} + b + \varepsilon \qquad (2a)$$

$$\text{if} \quad RDM_{i,j} < 30 \text{ then let } RDM_{i,j} = 30 \qquad (2b)$$

$$\text{if} \quad RDM_{i,j} > 200 \text{ then let } RDM_{i,j} = 200 \qquad (2c)$$

where,

$RDM_{i,j}$ is the i^{th} generated value of RDM for field j (cm);

$Al_{j,60\text{-}80}$ is the average value of $Al_{60\text{-}80}$ in field j (%);

a, b are regression coefficients calculated from the data in figure 12.1 (excluding data pairs with $Al_{60\text{-}80} < 25\%$): a= -2.565 cm $\%^{-1}$ and b=265.9 cm);

ε is a stochastic variable (cm) representing the deviation from the mean value of RDM, caused by spatial variation of Al^{3+} saturation in field j.

The results of chapter 4 showed that $Al_{60\text{-}80}$ presents considerable within-field variation in the Araras region, but spatial autocorrelation is weak for the sampling intervals that were considered. This, and the small number of sites in each field, prompted us to assume a Gaussian probability distribution for RDM, with average ε=0., and standard deviation S_{RDM}. S_{RDM} is estimated according to Helstrom (1991) from the standard

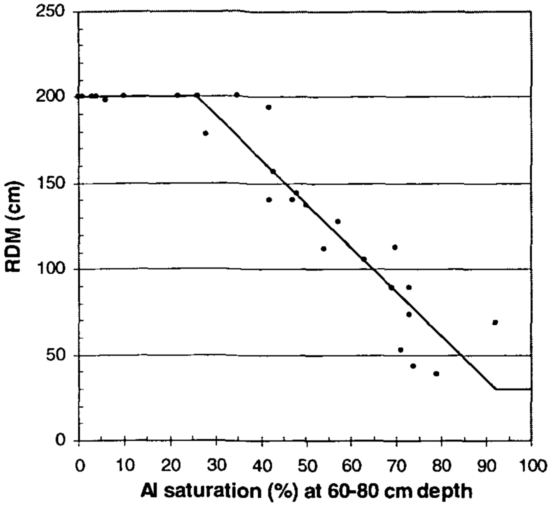


Figure 12.1

Estimated effective rootable depth (RDM) as a function of the Al^{3+} saturation at 60-80 cm depth (Al_{60-80}, %)

deviation of Al_{60-80} in field j ($S_{Al_{j,60-80}}$), the standard deviations of the coefficients a and b (S_a=1.181, S_b=70.14) of the regression equation (equation 2a), and the correlations between a and b ($r_{a,b}$=-.955; correlations a vs. Al_{60-80} and b vs. Al_{60-80} are 0.0 by definition):

$$S_{RDM}^2 = Al_{j,60-80}^2 S_a^2 + a^2 S_{Al_{j,60-80}}^2 + S_b^2 + 2Al_{j,60-80} S_a S_b r_{ab} \qquad (3)$$

$S_{Al_{j,60-80}}$ was approximated by the root pooled within field variance of Al_{60-80} (=14.98%). Results in table 4.1 suggest that within-field values of Al_{60-80} have an approximately normal distribution. The same was implicitly assumed for the residuals of equation 2a.

Note that equation 3 only considers uncertainties in estimated rooting depths as related to the lateral variability of Al^{3+} saturation and the use of the "pedo-transfer function" of equations 2. It ignores uncertainties incurred in the rather speculative estimation of RDM as a function of vertical changes in Al^{3+} saturation of the soil.

12.2.4 Generating water retention data

It was shown in chapter 6 that $\theta_{2d-1.5MPa}$ as inferred from tensiometer readings in the field and water retention curves in the lab, is significantly correlated with dry bulk density and total iron content of the soil. In chapter 7, it was suggested that if these data are not available, as is the case for the auger samples in this study, an average value of 0.17 $cm^3\ cm^{-3}$ can be substituted for $\theta_{2d-1.5MPa}$. The standard deviation ($S_{\theta_{2d-1.5MPa}}$) was 0.03 $cm^3\ cm^{-3}$. However, comparing gravimetrically determined field water contents with tensiometer readings and lab data (figure 6.1) suggested that the average value may be overestimated by up to 0.04 $cm^3\ cm^{-3}$.

The model proposed in chapter 11 requires input of the upper limit of available water [water stored in the soil after excess water is removed by drainage; in our case represented by θ_{2d} (cm^3 cm^{-3})], the lower limit of available water (estimated at $\theta_{-1.5MPa}$, cm^3 cm^{-3}), and an assessment of the water content of air-dry soil, θ_{AD} (cm^3 cm^{-3}). These data were generated as follows:

1. $\theta_{2d-1.5MPa}$ values were obtained by assuming a normal distribution with average values of either 0.17 or 0.13 cm^3 cm^{-3} and $S_{\theta_{2d-1.5MPa}}$ = 0.03 cm^3 cm^{-3}. To avoid nonsensical data, the generated values were bounded by a lower limit of 0.07 cm^3 cm^{-3} and an upper limit of 0.26 cm^3 cm^{-3};

2. $\theta_{-1.5MPa}$, i.e. the presumed lower boundary of available soil water (cm^3 cm^{-3}) is approximated with the transfer function derived in chapter 6 (Table 6.4, equation A):

   $$\theta_{-1.5MPa} = 0.02 + 0.27\,(\text{clay+silt}) \qquad (4a)$$

   where (clay+silt) is the average content of clay+silt (kg kg^{-1}) of the soil in the field;

3. θ_{2d} is calculated as

   $$\theta_{2d} = \theta_{2d-1.5MPa} + \theta_{-1.5MPa} \qquad (4b)$$

4. For the assessment of the air dry water content θ_{AD}, the so-called residual soil water content θ_r (c.f. Van Genuchten, 1980) was calculated according to chapter 7 (Table 7.3, equation A), as:

   $$\theta_r = 0.064 + 0.19\,(\text{clay+silt})^2 - 2.7\,10^2\,C_{org}^{\;2} \qquad (4c)$$

   where C_{org} is the organic carbon content (kg kg^{-1}). The calculated value was bound by the limits $0 \leq \theta_r \leq \theta_{-1.5MPa}$-0.005. θ_r was assumed to be retained at a soil water potential of -10 MPa; and 0.25 $\theta_{-1.5MPa}$ was assumed to correspond with a soil water potential of -100 MPa;

5. intermediate values were obtained by loglinear interpolation where necessary. In the current version of the model this is only used for the assessment of water contents of air-dry soil material, i.e. in equilibrium with the atmosphere.

12.2.5 Independent realisations from normal distributions

Independent random samples from normal distributions (to generate values for RDM and $\theta_{2d-1.5MPa}$) were simulated by first generating uniformly distributed random numbers with the FORTRAN RAN function and the RANØ subroutine described by Press et al, (1986). Transformation to a normal distribution was done according to Casella and Berger (1990).

$$t_1 = M_1 + S_1\cos(2\pi w_1)\sqrt{(-2\log(w_2))} \qquad (5a)$$

$$t_2 = M_2 + S_2\sin(2\pi w_1)\sqrt{(-2\log(w_2))} \qquad (5b)$$

where,

t_1,t_2 are uncorrelated drawings from normal distributions with means M_1 and M_2 and standard deviations S_1 and S_2 respectively;

w_1,w_2 are independent drawings from a uniform distribution.

Test runs (1000 x 2) suggested adequate approximation of a normal distribution without correlation between t_1 and t_2.

The t_1 values were always used to generate values for RDM ($M_1 = a.Al_{j,60\text{-}80} + b$ in eq. 2a; $S_1 = S_{RDM}$ in eq. 3) and the t_2 values were used to generate $\theta_{2d\text{-}1.5MPa}$ (M_2 =0.17 $cm^3.cm^{-3}$; $S_2 = S_{\theta 2d\text{-}1.5MPa} = 0.03\ cm^3.cm^{-3}$).

12.2.6 Model runs

The crop growth model presented in chapters 10 and 11 was used to calculate water-limited yield potentials of sugarcane for the following configurations:

1. RDM calculated stochastically according to equations 2a to 2c, with $\theta_{2d\text{-}1.5MPa}$ set to an average value of 0.17 $cm^3\ cm^{-3}$ and using method 1 for water uptake calculation;
2. Water retention data generated stochastically; RDM set to the average of the field (equation 2; ε set to 0.); method 1 for water uptake;
3. As 2., but with average $\theta_{2d\text{-}1.5MPa}$ set to 0.13 instead of 0.17;
4. Both water retention data (average $\theta_{2d\text{-}1.5MPa}$ set to 0.17) and RDM are generated stochastically; method 1 for water uptake;
5. As 4, but using method 2 for water uptake.
6. As 4, but with average $\theta_{2d\text{-}1.5MPa}$ set to 0.13 instead of 0.17;
7. As 4, but disregarding uncertainties related to the use of the transfer function (equations 2). This reduces equation 3 to $S_{RDM} \approx |a| * S_{Al_{j,60\text{-}80}} = 38$ cm.

The model was run 100 times for each harvest, which adds up to 7 x 81 x 100 runs. (± 7 hours run time PC, 266 Mhz). The average yield potential per harvest, Y_{sim} and the pooled standard deviation $S_{Y,sim}$ (root of mean of squared standard deviations) were calculated from the results of these test runs.

12.3 Results

The actual yield pooled standard deviation, i.e. the square root of the pooled variance of dry sugarcane yields among plots within a field S_{Yk}^2 (equation 1b) was calculated to be 2226 kg ha^{-1}.

Table 12.1 "Pooled" standard deviations of calculated yield potentials ($S_{Y,sim}$) for studied model configurations

Configuration		$S_{Y,sim}$ (kg ha^{-1})
1	RDM generated stochastically; $\theta_{2d\text{-}1.5MPa}$ = 0.17 $cm^3 cm^{-3}$; method 1 for water uptake.	3628
2	Water retention data generated stochastically; RDM set to field average; method 1 for water uptake.	1547
3	As 2., but with average $\theta_{2d\text{-}1.5MPa}$ set to 0.13 instead of 0.17	2264
4	Both water retention data (average $\theta_{2d\text{-}1.5MPa}$ set to 0.17) and RDM are generated stochastically; method 1 for water uptake;	3994
5	As 4, but with method 2 for water uptake.	3848
6	As 4, but with average $\theta_{2d\text{-}1.5MPa}$ set to 0.13 instead of 0.17	4436
7	As 4, but disregarding uncertainties in parameters *a* and *b* of equation 5.	3176

RDM, maximum rooting depth (cm); $\theta_{2d\text{-}1.5MPa}$, available soil water retained 2 days after field saturation ($cm^3 cm^{-3}$);

Table 12.1 presents the pooled standard deviations of yield potentials calculated with stochastically generated soil data ($S_{Y,sim}$). The values of $S_{Y,sim}$ suggest that uncertainties in rootable depth (configuration 1) have considerably greater effect on uncertainties in model outcomes than uncertainties in soil-water relations (configurations 2 and 3). Calculated yield variances resulting from these two sources of uncertainty exceed the variances in recorded yields among plots and are large in relation to the root mean square of residuals from regression between simulated yield potentials and actual yield records (4449 kg ha^{-1}) and the residuals from the 1:1 line as reported in chapter 11.

Uncertainties in model results are not homogeneous. For configuration 4, the smallest standard deviation among 100 runs was 67 kg ha^{-1} and the largest 8537 kg ha^{-1}. In one case, extreme vales of calculated dry cane yield potentials were 7600 and 49800 kg ha^{-1} ! Figure 12.2 (for configuration 4) shows that uncertainties are inversely correlated with RDM, i.e. sensitivity to RDM tends to become greater when RDM becomes more restrictive within the range studied. Comparing the differences in $S_{Y,sim}$ between configurations 3 and 2 with those of 6 and 4, also shows that uncertainties increase with decreasing $\theta_{2d\text{-}1.5MPa}$.

Figure 12.3 compares average model results for configurations 4 and 5. They are strongly correlated, but modelled yields for configuration 5 (water uptake method 2) are systematically smaller, with an average difference of 1500 kg ha^{-1}.

The average results for configurations 4 and 6, presented in figure 12.4, also show predominantly systematic differences.

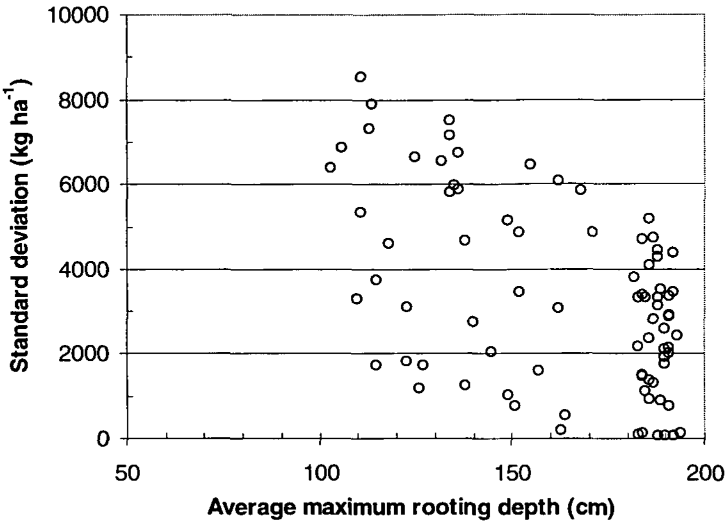


Figure 12.2 Standard deviations of calculated sugarcane yield potentials in relation to average maximum rooting depth (RDM) in model configuration 4. Results of 100 simulation runs were used to estimate each standard deviation

12.4 Discussion

The results presented in the foregoing clearly indicate that uncertainty propagation analysis be a standard practice for all cases studied, and not just be used as a preliminary sensitivity analysis for one or a few sample cases, because errors propagate differently for each crop. An extreme example to illustrate this point is given in figure 12.5, where calculated yield potentials for four consecutive harvests on field no. 2 are plotted against RDM, for four hypothetical values of $\theta_{2d\text{-}1.5MPa}$. Most curves tend to converge with increasing RDM, indicating a decreasing sensitivity of calculated yield potential to $\theta_{2d\text{-}1.5MPa}$. The decreasing steepness of the curves with increasing RDM and with increasing $\theta_{2d\text{-}1.5MPa}$ also points at decreasing sensitivity. However, the value of RDM where the curves level off, and the distances between the curves vary greatly among the scenarios. These variations are related to different rainfall distribution, evaporative demand and other growth conditions in the course of the growing season. Horizontal lines at the highest level would be expected in figure 12.5 if rainfall was sufficient and uniformly distributed, such as under drip irrigation. The divergent relations for the 3rd ratoon are attributed to an extreme dry spell during the summer of 1984, with only 59 mm rain in February + March. In ratoon cane, simulated cane yield potentials for equal values of total available water represented by the product RDM x $\theta_{2d\text{-}1.5MPa}$ cm (e.g. with RDM = 50 cm, $\theta_{2d\text{-}1.5MPa}$ = 0.26 vs. RDM = 100 cm, $\theta_{2d\text{-}1.5MPa}$ = 0.13) are generally slightly larger for smaller values of $\theta_{2d\text{-}1.5MPa}$. This is consistent with the competition between water uptake by roots and evaporation from the soil surface. When $\theta_{2d\text{-}1.5MPa}$ is large, a large proportion of infiltrating (rain)water is retained in the surface layer, where it is prone to evaporation. With smaller $\theta_{2d\text{-}1.5MPa}$ and deep rooting, infiltrating rainwater

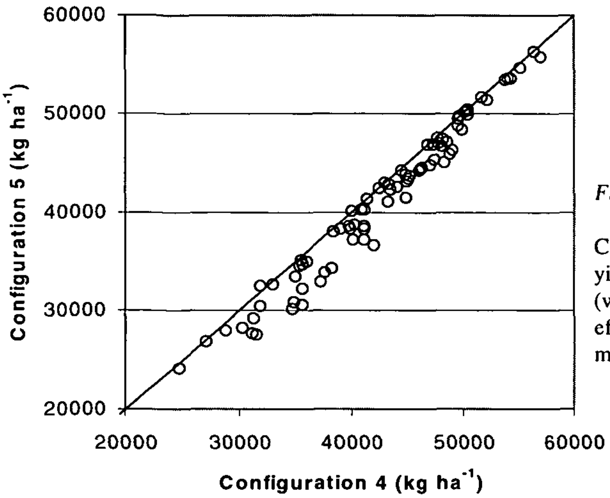


Figure 12.3

Comparison of average simulated sugarcane yield potentials, obtained for configuration 4 (water uptake method 1: with compensatory effects) and configuration 5 (water uptake method 2: no compensatory effects)

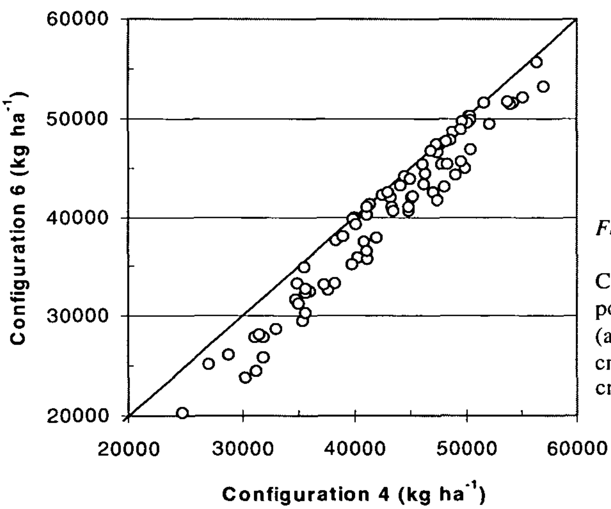


Figure 12.4

Comparison of calculated sugarcane yield potentials obtained for configuration 4 (average available water capacity = 0.17 $cm^3 cm^{-3}$), and configuration 6 (0.13 $cm^3 cm^{-3}$)

tends to percolate to deeper layers in the root zone, where it is still available to the roots, but protected against evapotranspiration. This interaction partly explain why uncertainties in $\theta_{2d\text{-}1.5MPa}$ have less effect on calculated yield potentials than uncertainties in RDM (see table 12.1). A more important reason for this is that the estimated uncertainty in $\theta_{2d\text{-}1.5MPa}$ is considerably less than that in RDM, even though $\theta_{2d\text{-}1.5MPa}$ is estimated as a simple average value.

It has been recognised for several decades that high Al^{3+} levels inhibit rooting and thereby water availability to crops. However, soil-water availability research on strongly weathered soils has mostly been concentrating on physical soil properties, partly because different crops and cultivars have different levels of tolerance and expensive crop monitoring field trials are necessary for quantified assessments and perhaps also because Al^{3+} research is traditionally the domain of soil fertility specialists, who are not familiar with soil water assessment. The results presented here suggest that systematic interdisciplinary research on these interactions may be rewarding.

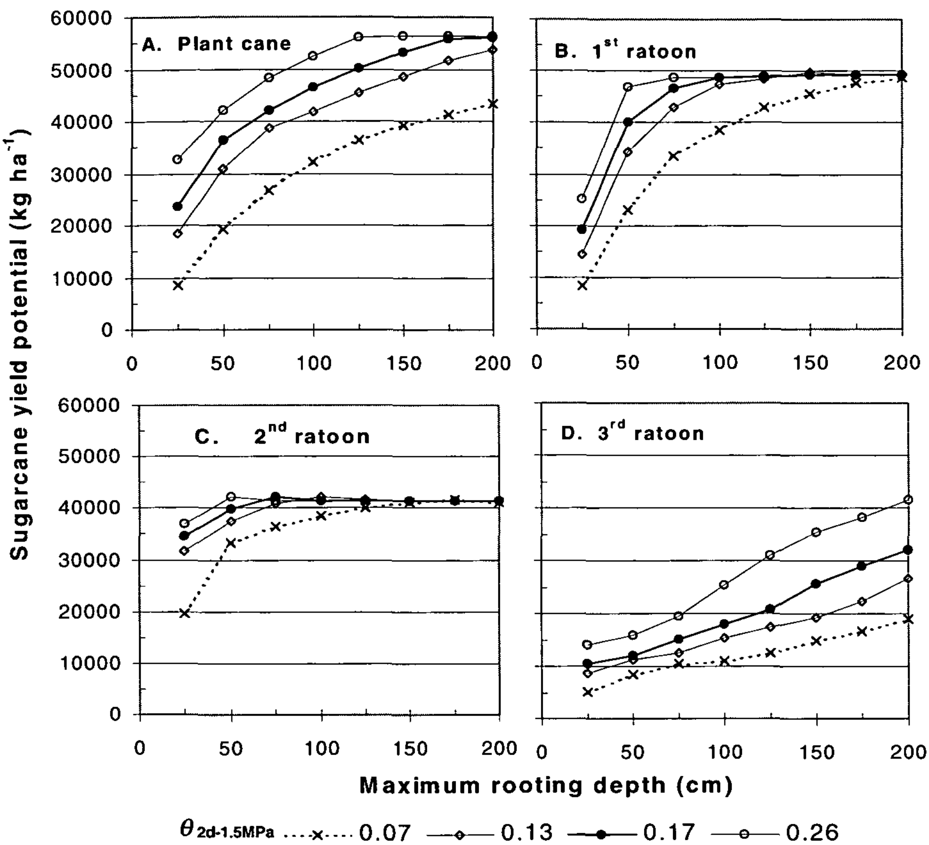


Figure 12.5 Simulated effect of maximum rooting depth (RDM, cm) and available water capacity ($\theta_{2d\text{-}1.5MPa}$, $cm^3 cm^{-3}$) on yield potentials of consecutive sugarcane crops at field 2. Day of planting: Feb. 16, 1980; 1st ratoon, July 11, 1981; 2nd ratoon, Sept. 23, 1982; 3rd ratoon, Sept. 13, 1983 - Sept. 15, 1984

Figures 12.3 and 12.4 showed that using different methods to calculate water uptake or to assess available water capacity results in systematic differences in calculated yield potentials. The differences are considerable, but the strong correlation between the results implies that it is not well possible to select a superior method on the basis of yield model results only. The hypothesis that water uptake is primarily conditioned by soil water status of the wettest zone is insufficiently tested. Almost all plant-soil-water research at the crop level is done by wetting the entire root zone followed by drying as crops withdraw water. This is fundamentally different from rainfed conditions, where wet and dry soil parts may occur together. The question of appropriate p_{soil} values, which was not addressed in this study, also deserves attention. E.g. Thompson (1976) suggests a fixed value of 0.5 for sugarcane, whereas Nable et al. (1999) found a value of 0.15 in a container experiment. Others prefer to determine p_{soil} as a function of atmospheric demand according to the method of Doorenbos and Kassam (1979) or according to the suggestions of Allen et al. (1998) as was done in this study.

12.5 Conclusions

1. For the situations examined, errors or uncertainties in both yield records from farmers' fields and the appraisal of water availability, strongly affect the relation between observed yields and calculated yield potentials.

2. To improve the relevance of crop growth models for studying the performance of rainfed sugarcane in the region, research on the rootability of the soil as affected by Al^{3+} saturation and its spatial variability deserves special attention in water availability studies.

3. Uncertainties in calculated yield potentials are different for each harvest but tend to increase when conditions become more limiting. They may vary by several orders of magnitude, even if the uncertainties in the input variables are kept constant. Therefore, uncertainty analysis should be a standard practice in land use systems analysis, and not just a preliminary study for one or few scenarios.

PART V

SYNTHESIS

13. PROSPECTS FOR QUANTIFIED METHODS OF LAND USE SYSTEMS ANALYSIS ON STRONGLY WEATHERED SOILS

13.1 Introduction

The general objectives of this research were (1) to increase the knowledge of the agricultural properties of strongly weathered soils and their spatial variability, and (2) to explore the potential of summary crop growth models and existing soil maps in modern (quantified) land use systems analysis at regional level. To accomplish these aims, several issues that were expected to affect the information stream from data collection to yield gap analysis were selected and studied in some detail. These issues were: (1) the spatial variability of soils and its relation to the quality of soil maps; (2) soil water relations; (3) summary model approaches to describe soil water uptake by plants, and (4) the distribution of assimilates over leaves, roots, stems, reproductive organs and stored reserves. These issues were integrated in chapter 11, where results of an adapted summary crop growth model were compared with on-farm yield records, and in chapter 12, which discussed how different types of errors or uncertainties in the appraisal of water availability may affect simulated yield potentials of sugarcane.

This chapter discusses the results of the study in the light of the general objectives. Section 13.2 discusses to which extent the objectives were accomplished, which insights were gained and which major problems were encountered. Suggestions are made on how problems could be tackled in future studies. Methodological aspects are discussed in section 13.3.

13.2 Achievements and persistent stumbling blocks

13.2.1 Spatial variability of strongly weathered soils and the quality of soil surveys

Results and implications for land use systems analysis

So far, few studies have addressed the spatial variability of strongly weathered soils and these were mostly confined to small experimental areas and concerned with a few soil characteristics only. Chapters 4 and 5 of this study considered the spatial variability of a score of soil characteristics at a regional level. It was hypothesised that similar strongly weathered soils in different regions would possibly present similar structures of spatial variability. This would be of great help in understanding the relations between soil patterns and soil processes, and in optimising sampling schemes in future surveys.

This study has shown that, even though absolute differences between the study regions were sometimes large, some clear trends could be recognised: particle size distribution, CEC and organic matter content showed little variability within 1000 m, whereas base saturation, Al saturation and resin extractable P present so much short range (within 50 m) variability that traditional methods of soil survey (drawing boundaries on landscape features, point augering and occasional profile sampling) seem inadequate to reveal spatial patterns at regional level. This was confirmed by the purity analysis on published soil maps (chapter 5). The results of chapter 4 also suggest that different management practices for different crops (sugarcane and soybean) are associated with considerable differences in the spatial variability of soil properties of the surface layer and, in some cases, even of the 60-80 cm layer.

The soil maps studied differentiate soils adequately on the basis of taxonomic criteria such as type of B-horizon; texture class and clay activity. However, the maps provide hardly any useful information on the chemical properties of the surface layer of the soils studied and are little informative with respect to the trophic character (base status and Al^{3+} saturation of subsurface soil). As available water capacity estimates appeared to be poorly correlated with soil texture (chapters 5 and 6), it is concluded that the studied (1 : 100 000) soil maps and the accompanying reports have little to offer to differentiate strongly weathered soils with respect to their production potential. The results suggest that much more detailed and costly sampling would be necessary for this purpose. This does not mean that standard soil maps are generally unsuitable for land evaluation. This study focused on the production potential which is just one (important) land quality. For example, soils with a textural B-horizon are more sensitive to erosion than most soils with a Latosolic B (Lombardi & Bertoni, 1975); soils with large CEC require different fertilizer management than low activity soils. Strongly weathered soils with a sandy texture may have little natural fertility, but better trafficability in wet conditions than clayey soils (Demattê, 1988), which is the main reason why sugarcane mills in the study regions grow cane on clayey and sandy soils, even if the latter are sited at large distance from the mill. These areas are needed to keep the mill running during rainy periods in the harvest season. The important land qualities "trafficability", "natural fertility" and "erodibility" can be inferred from soil maps, but often they cannot (yet) be used for quantified assessment of land suitability.

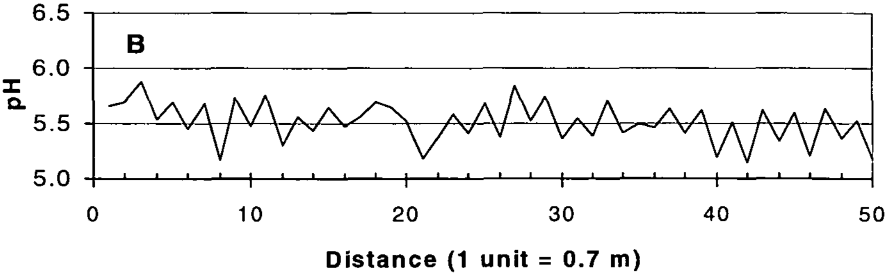


Figure 13.1 Observations along a transect perpendicular to sugarcane rows. Even numbers (above tick marks) on-rows; odd numbers between rows. A: number of blows to penetrate 30-60 cm layer; B: pH at 60-80 cm depth

Suggestions for further research

Additional studies on medium range (0.5-3km) and short range (<50m) soil variability are needed to optimize sampling schemes, and to reveal the causes of soil variability. Medium range structures can perhaps better be identified if larger areas (say 10x10 m) are examined using bulk sampling instead of single point sampling. However, the merits and limitations of bulk-sampling for soil surveys need further research. It may facilitate the design of uniform mapping units, but the homogeneity will be illusionary. A preliminary study of the short range variability of soil-pH and penetrometer resistance on commercially grown sugarcane fields showed that most of the variability present within the 50 m distance is also present within 1 m. The results in figure 13.1 suggest that the principal cause of this variability is management. Little is known about the impact of such short-range variability on crop growth. Should models take account of this or is it possible to account for this by using compound "effective" values?

Another important research item is the correlation between easily mappable soil properties such as field texture and difficult properties such as soil acidity and related Al saturation. It was observed in chapter 5 that sandy soils tend to be more acid than clayey ones. This is further illustrated in Figure 13.2.

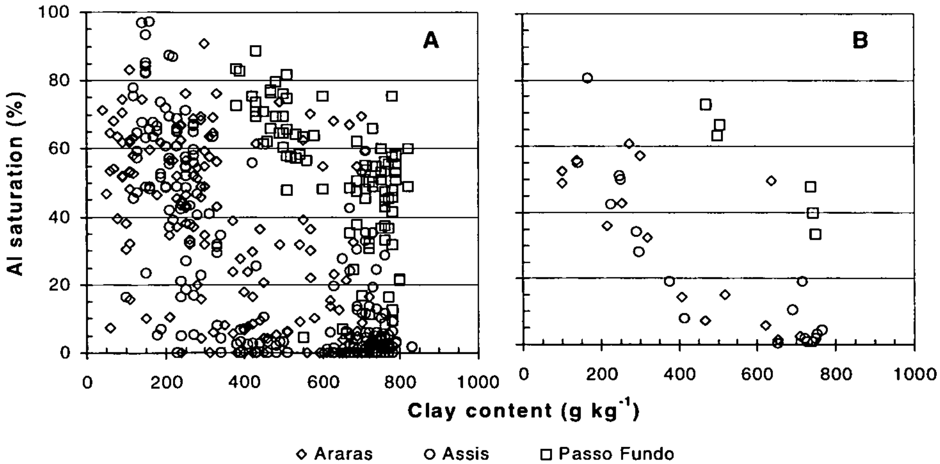


Figure 13.2 Al-saturation vs. clay content of soil samples from 60-80 cm depth. A: single values; B: field averages

Figure 13.2a presents a scatter plot of Al-saturation at 60-80 cm depth vs. clay content. The correlation between these soil characteristics becomes much more evident after averaging by field (Figure 13.2b). This again illustrates how the smoothing effect of bulk sampling may improve estimates of chemical soil characteristics and at a reasonable price.

The causes of these phenomena and their consistency need further investigation. A plausible reason why sandy soils in the study regions tend to be more acid than clayey ones is that the first are derived from sedimentary rocks, with a large proportion of quartz and few weatherable silicate minerals, and consequently a very low buffering capacity. Lime, originally present in some of the Mesozoic sandy sediments (IPT, 1981), may have been leached rapidly (at a geologic time scale). The clayey soils in the study regions are derived from basalt and intrusive rocks with a "rich" composition. The reason why soils of the Passo Fundo region tend to be more acid than those of the Araras and Assis regions may be connected with climatic differences, e.g. more intensive leaching in the perhumid Passo Fundo region. Recall that the clayey soils of the three regions are derived from the same geologic Serra Geral formation.

13.2.2 Soil-water relations

Results and implications for land use systems analysis

Soil-water relations of strongly weathered soils have been studied by a small but very active group of Brazilian scientists. Most published work refers to the analysis of plant-soil-water relations in the laboratory and the spatial variability of related soil characteristics in experimental fields. The present study considers a variety of strongly weathered soils, permitting to make some general statements on soil-water relations in the study regions. Some of these confirm the findings of earlier work, mostly on a much narrower range of soils; others show that generalised statements on strongly weathered soils should not be uncritically accepted for application in specific regions:

- The water retention curves of all soils in the present study can be adequately described with the "Van Genuchten equation" (see also Villagra et al., 1988).

- Field-measured water contents at specific matric potentials are consistently smaller (upto some 0.04 $cm^3 cm^{-3}$) than water contents determined in the laboratory (see also Uehara & Gilman, 1981; and Freire, 1979).

- Available water capacity (AWC, the soil water held in range from -1.5 MPa to field capacity) is related to sesquioxide content and particle size distribution and is conditioned by the presence of dense layers. AWC predictions based on soil texture alone yield poor estimates (see also Wolf, 1975; Van den Berg et al., 1997; Tomasella & Hodnett, 1998).

- Values of AWC of the soils studied are considerably greater than the indicative 0.1 $cm^3 cm^{-3}$ often mentioned for strongly weathered soils in general (Lal, 1979; ISSS Working Group RB, 1998b; Batjes, 1996), but are well in line with the lysimeter data mentioned by Carlesso & Santos (1999).

- Transfer functions to predict key soil-water contents of well drained, strongly weathered soils should be based on direct correlation against relevant soil parameters, rather than on a descriptive equation (see also Van den Berg et al, 1997).

- The field capacity concept can be applied in the study regions to assess available water in summary crop growth models.
- Identifying the permanent wilting point with the water retained at -1.5 MPA may be less appropriate for strongly weathered soils than generally assumed.

These results suggest that simple water distribution routines can be used in summary crop growth models for the assessment of crop yield potentials on well-drained strongly weathered soils but special attention is needed to the determination of the quantity of available water that can be stored in the rooted soil.

Suggestions for further research

Discrepancies between lab and field measurements and the permanent wilting point concept need to be investigated more systematically. This can only be done by well-controlled field experiments and monitoring of water dynamics. Today, this is within reach for most research institutes thanks to the availability of automatic TDR equipment at affordable prices. The results of such experiments must be correlated against laboratory data, to evaluate to what extent these are of value.

Soil-air relations and mechanical characteristics form further points of concern. Latosols under natural conditions have proverbially favourable physical characteristics with respect to aeration, workability and root penetration. Soil compaction problems as encountered (mainly) in Passo Fundo, seem to be the product of inadequate management and have been blamed on tillage of wet soils and excessive lime application (Klamt et al., 1983, Westerhof et al., 1999). The first aspect seems of more importance under the perhumid conditions of Passo Fundo. Since the late 1980's, direct drilling (zero-tillage) is being adopted as the new paradigm in soil management to prevent degradation (Freitas, 1999) but remedy remains a difficult task. The great sensitivity to aeration of the (simple) model applied, and the complex nature of the real problem are reflected by inconsistent response to changes in model parameters suggesting that a much more refined approach is necessary to model crop growth under transient anaerobic conditions.

13.2.3 Summary model approaches to describe water uptake by plants

Results and implications for land use systems analysis

The qualitative analysis of simple approaches to describe water uptake by plants presented in chapter 8, and the quantitative comparison of three models in chapter 9 show that different methods can produce considerably different estimates. The results suggest that, for land use systems analysis, simple approaches are preferred over complex process-based ones, because the former need less data and there is no evidence that the latter are more accurate. Uncertainties with respect to related model parameters and the question to which extent the heterogeneous soil water distribution affects water uptake by crops can be studied by running models under different "what if" assumptions and comparing the results.

Suggestions for further research

It is necessary to investigate if simple relations can consistently describe the effects of soil water status on water withdrawal by plants. Comparison of the vast amount of available literature is hampered by the incoherent use of terminology and methodological diversity. The importance of compensatory effects in water uptake, when soil water is non-uniformly distributed, is another point of concern. Such research could be combined with the studies suggested in section 13.2.2.

13.2.4 Summary model approaches to assimilate partitioning over crop components

Results and implications for land use systems analysis

The theoretical considerations presented in chapter 10 illustrate the need to consider the effects of external incentives on the distribution of newly formed (or remobilized) assimilates over plant organs. The results of the model exercises suggest that this is possible, even in summary crop growth models, by acknowledging that crops tend to optimise assimilate partitioning and that changes over the growing season provoke adaptive responses within limits set by the genetic blue print.

Suggestions for further research

Further research is necessary to evaluate the approach proposed and to determine which refinements are necessary. Special attention should be given to sink-limited growth of crop components, the impact of water excess and recuperation times under alternating stress conditions.

13.2.5 Application of summary crop growth models in analysis of land use systems on strongly weathered soils

Results

The potential of dynamic summary crop growth models for land-use systems analysis in tropical regions was addressed in chapters 11 and 12, where a summary crop growth model was tested and the propagation of errors and uncertainties assessed. The results showed that such models must preferably not be used to predict individual yields on individual fields, but regional yield potentials by year or averaged long term yield potentials on specific fields could be assessed after calibration. Similar results were reported by Dumanski and Onofrei (1989) who found excellent correlation (r^2>0.95) between modelled and averaged grain yield records of experimental plots in Canada. Long term averages are highly relevant to regional land development studies, but the results obtained so far are too incipient to be used in (yield failure) risk analysis or for the construction of yield probability density functions. The modelling exercises also illustrated that simulation can be an eye-opener to indicate alternative management opportunities. The model calculations suggested that timing of sugarcane planting and ratooning is very important with regard to the development of the new crop, whereas traditionally sugarcane management is focused on the timing of harvesting with regard to the quality of the standing crop. The model results were confirmed by the field data for Araras, but not for Assis.

These and other results of chapter 11 confirm once more that parameter values must be established carefully and recalibration and field-testing are necessary when new areas are assessed (see also Sinclair & Seligman, 1996). This is a serious limitation of "summary" models that often claim wide applicability (e.g. Bannink et al., 1988; Palmer, 1983; Van Lanen, 1991) because the experiments needed to establish parameter values are expensive and tedious. Land evaluators are confronted with the choice between simple qualitative methods that produce general and possibly subjective answers, and quantified methods, whereby the latter can often only be run with data of unknown integrity, and hence produce results of unknown quality. The need for quantified information pushes methodological work towards dynamic systems analysis and user-friendly computer implemented crop growth models linked to GIS and the internet are increasingly available. Third parties, who were not involved in model development and testing, are tempted to apply the models to analyse their problems, but few people are able to judge the relevance of a particular simulation model for a particular application. Guidelines may be formulated to restrict the use of crop models for their specific objectives, providing the following information:

- the situation for which the model was initially developed;
- the type of application for which the model is intended [e.g. land evaluation, land use planning (at which scale?), exploratory studies, on-farm decision support, education, research];
- the boundary conditions; e.g. biophysical production potential; water-limited production potential (with or without groundwater and aeration); nutrient-limited production potential (which nutrients, toxicity); extent to which empirical relations are used and major uncertainties;
- the situation(s) for which the model was tested (soil types, climate, crops, range of planting dates); how independent were test results from calibrations;
- the situations to which the model can be applied without hesitation; situations where additional experiments are necessary; situations where it should not be used at all.

All this demonstrates that dynamic systems analysis may continue to be a suitable tool in land evaluation but under very strict rules such as applicability, ownership etc. which should be formulated. Besides, there is no attractive alternative. Simpler parametric methods are less transportable and lack the potential for making detailed risk analyses. A modest attitude is necessary however. Predictions based on crop growth modelling are subject to failure, just as much as economic projections or weather forecasts. Improvements are obtained gradually by feedback between research, model development and application. Eventually simplified crop/environment relations with wide applicability may be formulated, so that perhaps future models will need less calibration. An example is the algorithm proposed in chapter 10 which replaces the tabulated relation between development stage and assimilate distribution. The approach is promising, but needs further experimental support.

Suggestions for further research

Bull & Tovey (1974), pioneers of sugarcane growth modelling, state that "perhaps the most pertinent fact emerging from the attempt to construct a model is just how little is known...". This feeling still existed when this research was finished, more than 25 years later. Much is known of the functioning of plant organs but quantitative knowledge of the effects of a changing environment on crop behaviour is still primordial.

It makes little sense to continue developing "summary" models and, at the same time, complain about the lack of accurate test data. Detailed, well-controlled experiments to determine biophysical yield potentials, water-limited potentials and nutrient-limited potentials are needed. Development of quantified operational methods to describe the relation(s) between Al^{3+} concentration (or saturation), rooting patterns and water availability is of special importance to land use systems on strongly weathered soils. Much research should be done in the field, by monitoring crop growth and water dynamics under a variety of environments. Such experiments are costly and time consuming, but necessary. This could be facilitated if data exchange between researchers were attractive to those who conduct the experiments.

13.3 Methodological aspects

This research was based on the notion that a holistic approach is needed to "understand" strongly weathered soils and to assess the potential of quantified land evaluation. Therefore the study has an exploratory nature, and consequently some interesting subjects, that deserve more detailed research, were left aside or were only superficially addressed. The study was conducted on commercial farms rather than on experimental fields because (1) on-farm results were assumed to have the greatest practical value; (2) farmers involved expressed a great interest to participate and helped out with tractors, trucks and manpower; (3) experimental fields are small and their management history is too variable to permit analysis of spatial variability at a regional scale; (4) it would have been impossible to collect the yield data needed for this study; (5) it would have been impossible to find the diversity of strongly weathered soils analysed in this study within one experimental station. The major disadvantage of the adopted methodology is that the on-farm data refer to a less well controlled environment, making it impossible to check to which extent yield potentials calculated in the modelling exercises correspond to realistically attainable yields. Attempts to carry out on-farm crop monitoring experiments for this purpose proved to be too ambitious for this study, considering the limited available manpower and equipment.

An interesting approach which combines on-farm monitoring and simulation, and which also relies on the participation of farmers and the extension sector has been adopted by the Agricultural Production Systems Research Unit of CSIRO, Australia.

Farmers set aside part of their land to conduct simple attainable yield trials in close co-operation with researchers. Results presented by Robertson et al. (2000) clearly illustrate the strength of the approach, including the feedback between researchers, modellers and farmers, developing an upward spiral of objective oriented research, model improvement, improved assessment of management opportunities, identification of discrepancies etc. The present study in Brazil and personal experience have taught that extension workers and farmers with higher education are eager to participate and suggest that research capacity and technology are available to make a similar approach work in central and southern Brazil.

It may be argued that high-input land use systems as considered in this study are not representative of "tropical agriculture", which is often identified with subsistence farming. Apart from the fact that low external input sustainable agriculture is questionable on strongly weathered soils in Brazil and elsewhere (Borlaug & Dowswell, 1997) it would have been impossible to conduct this study on small holders' farms because (1) records on past yields and management would not have been available; (2) the influence of diseases, pests, nutritional disorders, poor quality seed, etc. would have increased yield variability so that comparison of yield potentials with observed yields would have been impaired; (3) logistic problems would have been much greater.

Another aspect of the research approach adopted is that the same data were used for different kinds of analysis. The strength of this integration is that results on different aspects of land use systems are directly linked. There are also some reservations: it is virtually impossible to find in the real world conditions that are suited to study a great variety of aspects without the risk to confound causes and consequences. For example, the soybean and sugarcane fields in Assis are not randomly distributed. It was postulated that differences in surface soil characteristics are mainly due to long-term management, because subsurface horizons are very similar. Another concern is the position of soil profiles in the study fields. These were selected to represent the modal characteristics of the fields; however, their selection was restricted, because the same profiles were used for the soil water study, which required a more or less level surface.

13.4 Application of results to other regions with similar soils

Brazilian strongly weathered soils are not the same as, for example, sub-Saharan African ones, but there are many similarities (Sanchez, 1998). Problems related to soil acidity, P fixation and low CEC are inherent to these soils, but they are in general somewhat less pronounced in southern Africa, probably thanks to admixtures of dust from volcanic or Saharan origin and a less humid climate. Comparison with findings from different regions (e.g. table 6.1) is difficult, because methods used to determine different soil characteristics are not uniformly applied.

It is expected that most results can serve as a reference point for studies in these regions, but the findings need to be confirmed.

SUMMARY

Strongly weathered red-yellow to dusky red soils of the tropics occupy more than 40 percent of the global arable area, predominantly in Latin America and Tropical Africa. A considerable part of these soils occurs under natural rainforest, wood and savannah-like vegetation. Another large part is used extensively for crop production and grazing, with very low yield levels. Textbooks frequently characterise these soils as chemically extremely poor and having a small available water capacity, resulting in relatively large yield declines as a consequence of short periods of drought.

In previous decades, especially in Brazil, it has been shown that many of these soils can produce excellent yields if they are limed and properly fertilised. This has caused agricultural intensification and an enormous expansion of agricultural land use, especially with soybeans, citrus and sugarcane. Negative consequences of these developments are the accelerated destruction of natural ecosystems and soil degradation. Several attempts to undertake profitable agriculture on similar soils in the Amazon region have failed completely.

The principal objectives of this study were: (1) to increase the knowledge of the agricultural properties of strongly weathered soils and their spatial variability, and (2) to explore the potential of existing, or somewhat adapted means and methodologies to assess biophysically obtainable production levels of land use systems envisaged on these soils. Such assessments could assist in making well-balanced rational choices with respect to e.g. agricultural intensification, area expansion or nature conservation. Special attention is given to the usefulness of currently available soil information (maps and accompanying reports) and computer-based crop growth simulation models.

The research was conducted in two regions of São Paulo State and one region in Rio Grande do Sul. The soils of a total of 42 fields of agricultural enterprises were examined. Of these fields, 28 had been cropped intensively with sugarcane and 14 with soybean during the summer months and (usually) wheat during winter. The growth of three popular soybean cultivars was monitored in one field. The soil data collected were analysed using (spatial) statistics and they were compared with information on published semi-detailed soil maps (1:100 000). A modified version of the crop growth model PS123, which is being developed at Wageningen University to support land use systems analysis, was used. The resulting model was calibrated for the soybean monitoring experiment and published sugarcane experiments, and then used to calculate yield potentials which were compared with on-farm yield records from the participating enterprises.

The results of the research revealed some interesting similarities and differences between soil patterns in the research regions. Contents of clay and organic matter, and also the cation exchange capacity related herewith, show little variation over short to medium distances (< 1000 m). Short range (< 50 m) variation was very great however with respect to the trophic character (base and aluminium saturation), except for the subsoil of the fields studied in Rio Grande do Sul, which was invariably acid and poor. The topsoil, affected by

management, usually presented more variability in the sugarcane fields than in the soybean fields which are frequently homogenised by tillage.

The quality of the soil maps studied was found to be strongly related to the level of short range variability. Soil texture classes were usually adequately mapped, but the trophic character was either displayed in very general terms or with considerable errors. Improved mapping of this important soil property would become very expensive with current sampling methods but may become feasible when taking better advantage of regional correlations between easily-mappable soil properties and soil properties that are difficult to map. In addition, visualisation of medium- and long-distance soil variation can possibly be improved by using bulk sampling to remove short range variation.

Results of the analysis of soil-water relations suggest that the physical aspects of water availability of the soils studied are considerably more favourable than is often generalised in textbooks. In contrast to many soils of temperate regions, available water capacity of the studied soils is only weakly correlated with easily-measured soil characteristics such as contents of clay and sand. Predicting such difficult-to-measure data is therefore difficult. In some cases, simple averages are more accurate than results obtained by semi-theoretical parametric methods.

The results of this study and revision of available literature illustrate the usefulness of crop growth simulation for land use systems analysis. The crop growth model used calculates considerably higher yields in favourable years than recorded on-farm yields. This suggests that intensification of crop management may be an attractive option. However, uncertainties in the yield gap assessment are great because practically available data, as well as crop growth models, are incomplete and contain errors and uncertainties which require additional fieldwork and/or simplifying assumptions. In contrast to what is often suggested, models should always be tested and occasionally be adapted to cope with new situations. There is little sense in making statements about attainable yields without indicating the assumptions on which they are based and to which extent uncertainties may affect the results. For land use systems modelling, stochastic simulation methods were applied to assess the range of uncertainty in model outputs as a result of variations in the input data. The uncertainty analyses were used to explore error propagation in water availability assessment as related to calculated sugarcane yield potentials. The results indicate that, with respect to water availability of the studied soils, root growth limitation by chemical barriers may have caused stronger soil differentiation than physical soil properties. Systematic objective oriented research, in close co-operation with farmers and other stakeholders, is essential (and practicable) for a step-by-step improvement of the applicability of the mentioned tools to biophysical land use systems analysis, contributing to the efficient and sustainable use of strongly weathered soils.

SAMENVATTING

Sterk verweerde tropische gronden, met hun typerende geel/rode tot diep donkerrode kleur, beslaan meer dan 40% van het wereldareaal bodems dat voor landbouw in aanmerking komt. Deze gronden komen vooral veel voor in Latijns Amerika en Tropisch Afrika. Een groot deel ligt nog onder natuurlijke (regenwoud, bos en savanne-achtige) vegetatie, en een ander groot gedeelte wordt extensief gebruikt voor landbouw en veeteelt, met zeer lage opbrengsten. In tekstboeken worden deze gronden vaak omschreven als chemisch zeer arm en met een gering waterleverend vermogen, waardoor een korte periode van droogte tot relatief grote opbrengstderving kan leiden.

In de afgelopen decennia is met name in zuid en zuidoost Brazilië aangetoond dat veel van deze gronden uitstekende opbrengsten kunnen voortbrengen, mits zij worden bekalkt en bemest. Dit heeft geleid tot intensivering en tot een enorme toename van het landbouwareaal, m.n. soja, citrus en suikerriet. Negatieve gevolgen zijn echter een versnelde vernietiging van natuurlijke ecosystemen en bodemdegradatie. Pogingen om winstgevende landbouwondernemingen op soortgelijke gronden in het Amazonegebied op te starten zijn veelal op een mislukking uitgelopen.

Hoofddoelen van deze studie waren: (1) Een betere karakterisering van de landbouwkundige kwaliteiten van deze bodems en hun ruimtelijke variabiliteit en (2) te onderzoeken hoe bestaande, of enigszins aangepaste, middelen en technieken kunnen worden ingezet om het productiepotentieel van beoogde landgebruikssystemen op deze gronden beter in te schatten. Hierdoor zouden beslissingen tot bijvoorbeeld intensivering, uitbreiding of natuurbescherming op meer rationele afwegingen gebaseerd kunnen worden. Er is met name gekeken naar de bruikbaarheid van bestaande bodeminformatie (kaarten en bijbehorende rapporten) en computermodellen voor gewasgroei-simulatie.

Het onderzoek is uitgevoerd in twee gebieden in de Braziliaanse deelstaat São Paulo en één gebied in Rio Grande do Sul. De bodems van in totaal 42 percelen van landbouwbedrijven werden onderzocht. Van deze percelen waren 28 intensief bebouwd met suikerriet en 14 met soja in de zomer en (doorgaans) tarwe in de winter. Op één perceel werd de groei van drie populaire soja variëteiten gevolgd. De verzamelde bodemgegevens werden met (ruimtelijke) statistische methodes geanalyseerd en (die van de deelstaat São Paulo) vergeleken met de informatie weergegeven op semi-gedetailleerde bodemkaarten (1:100 000). Het gebruikte gewasgroeimodel is een aangepaste versie van PS123, dat aan Wageningen Universiteit wordt ontwikkeld voor biofysische analyses van landgebruiks-systemen. Dit werd gekalibreerd voor het soja-monitoring-experiment en eerder gepubliceerde suikerriet experimenten en vervolgens gebruikt om potentiële opbrengsten te berekenen die werden vergeleken met opbrengstgegevens van de samenwerkende bedrijven.

De resultaten van het onderzoek onthulden interessante overeenkomsten en verschillen tussen bodempatronen in de verschillende onderzoeksgebieden. Gehaltes aan klei en organische stof en ook de hiermee samenhangende kationenuitwisselingscapaciteit tonen weinig variatie op korte en middellange afstand (< 1000 m). De korte-afstand variatie (< 50 m) was juist erg groot wat het trofisch karakter betreft (verzadiging in basen en

aluminium). Dit laatste geldt echter niet voor de ondergrond van de onderzochte percelen in Rio Grande do Sul, die altijd arm en zuur was. De door management beïnvloede bovengrond van de percelen met suikerriet toonde doorgaans meer variatie dan de bovengrond van de percelen met soja die veel vaker door bewerking wordt gemengd.

De kwaliteit van de bestudeerde bodemkaarten bleek sterk samen te hangen met de korte afstand variabiliteit. Textuur-klasses zijn doorgaans correct in kaart gebracht, terwijl het trofisch karakter óf slechts zeer globaal of met aanzienlijke fouten wordt weergegeven. Het beter karteren van deze belangrijke bodemeigenschap zal met de gebruikelijke bemonsteringsmethodes zeer hoge kosten met zich meebrengen. Men zou echter beter gebruik kunnen maken van regionale correlaties tussen gemakkelijk- en moeilijk karteerbare bodemeigenschappen. Bovendien kan de midden- en lange-afstandsvariabiliteit wellicht beter in kaart worden gebracht, door met mengmonsters de korte-afstandsvariabiliteit in het kaartbeeld te onderdrukken.

De resultaten van het onderzoek naar bodem-water relaties suggereren dat de fysische aspecten van het waterleverend vermogen van de onderzochte bodems aanmerkelijk gunstiger zijn dan in de tekstboeken wordt gegeneraliseerd. De hoeveelheid beschikbaar water per eenheid bodemdiepte lijkt nauwelijks gerelateerd te zijn aan eenvoudig te bepalen bodemeigenschappen zoals het zand en klei gehalte, hetgeen bij bodems van gematigde streken vaak wel het geval is. Voorspellen van deze moeilijk meetbare bodemeigenschap is daardoor problematisch. In sommige gevallen blijken simpele gemiddelde waardes nauwkeuriger te zijn dan de met behulp van semi-theoretische parametrische methodes verkregen resultaten.

De bruikbaarheid van gewasgroeisimulatie voor de analyse van landgebruikssystemen wordt aan de hand van literatuur-revisie en de verkregen resultaten geïllustreerd. Het gebruikte model berekent in gunstige jaren aanmerkelijk hogere opbrengsten dan de bedrijfsresultaten, waardoor er ruimte lijkt te zijn voor productieverhoging. Onzekerheden in de berekende waardes zijn echter groot omdat zowel de in de praktijk beschikbare gegevens als de gewasgroeimodellen lacunes, fouten en onzekerheden bevatten waardoor aanvullend veldwerk en/of versimpelende aannames nodig zijn. In tegenstelling tot wat veelal wordt gesuggereerd moeten modellen voor nieuwe situaties steeds worden getest en evt. aangepast. Het heeft weinig zin om uitspraken te doen over haalbare gewasopbrengsten zonder aan te geven op welke aannames deze uitspraken berusten en in hoeverre onzekerheden de resultaten kunnen hebben beïnvloed. Voor modellering van landgebruikssytemen werden stochastische simulatiemethodes gebruikt voor het inschatten van onzekerheden in modeluitkomsten als gevolg van fouten/onzekerheden in invoergegevens. Deze analyse werd uitgevoerd om de voortplanting van onzekerheden betreffende de waterhuishouding van de onderzochte bodems in relatie tot berekende suikerrietopbrengsten te verkennen. De resultaten suggereren dat, qua beschikbaar vocht, beperking van de beworteling door chemische barrières de bodems sterker differentiëren dan fysische bodemeigenschappen. Systematisch doelgericht onderzoek, in nauwe samenwerking met landbouwers en andere belanghebbenden, is essentieel (en uitvoerbaar) om de praktische inzetbaarheid van de genoemde technieken voor biofysische analyse van landgebruikssystemen stapsgewijs te verbeteren en zo bij te dragen aan een duurzaam efficiënt gebruik van sterk verweerde gronden.

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APPENDIX 1. Calculation of soil water depletion fractions in WOFOST and SUCROS

WOFOST

WOFOST (Supit et al., 1994; Boogaard et al., 1998) uses the following equations to calculate depletion factors (p), in dependence of crop group (N_{cg}), and maximum evapotranspiration (ET_m, cm):

$$p = 1/(0.76 + 1.5*ET_m) - 0.1*(5-N_{cg}) \quad \text{(A1.1)}$$

For crop groups 1 and 2, an additional correction is applied to reproduce the tabulated values of Doorenbos et al. (1978) correctly:

$$p = p + (ET_m - 0.6)/(N_{cg}*(N_{cg}+3)) \quad \text{(A1.2)}$$

SUCROS

Keulen et al (1997), referring to Driessen (1986)[1] calculate p values as:

$$p = T_{\Theta r=0.5}/(T_m + T_{\Theta r=0.5}) \quad \text{(A1.3)}$$

where $T_{\Theta r=0.5}$ is the crop-group specific transpiration rate at which $p = 0.5$, i.e. θ_c exactly halfway θ_{fc} and θ_{pwp}. Note that, according to equation (A1.3), p is close to 1. in case of an emerging crop.

Characteristic values of $T_{\Theta r=0.5}$ are given in table A1.1, according to Keulen et al (1997, citing Driessen, 1986[1] and Doorenbos et al., 1978). Related p values, given by Supit et al (1994), citing Doorenbos et al., (1978), are also given in table A1.1.

Table A1.1. Characteristic values of $T_{\Theta r=0.5}$ for 5 crop groups and of p in dependence of ET_m. Sources: see text.

Crop group	Crops (examples)	$T_{\Theta r=0.5}$ (cm.d^{-1})	ET_m (cm.d^{-1}) 0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
			←				p values				→
1	Leaf vegetables	0.18	.45	.38	.30	.25	.23	.20	.18	.16	.15
2	Clover, carrot	0.3	.60	.50	.43	.35	.30	.28	.25	.23	.20
3	Grape, pea, potato	0.45	.75	.65	.55	.45	.40	.38	.33	.30	.25
4	Citrus, groundnut	0.6	.85	.75	.65	.55	.50	.48	.43	.38	.35
5	Sugarcane, soybean, sorghum	0.9	.92	.85	.75	.65	.60	.55	.50	.48	.45

Keulen et al. (1997) show that, by substituting f_r by T_a/T_m and rearranging equations 9.4 (of chapter 9) and (A1.3), T_a can also be calculated directly:

$$T_a = \mathrm{MIN}(T_m,\ (T_m + T_{\Theta r=0.5}) * \Theta_r) \quad \text{(A1.4)}$$

[1] The described method was not encountered in the referred publication of Driessen (1986).

APPENDIX 2. Implementation of water balance module in adapted PS123 model

Representation of the rooted soil and initial settings

The soil is divided in compartments. Each compartment has a user-defined thickness D_{max} (cm), except the deepest one. The lower boundary of that compartment accompanies the lower boundary of the root system. A new lower compartment is initialised when downward extension of the rooted zone induces the thickness of the deepest compartment to exceed D_{max}.

Downward extension of the root system is assumed to proceed at a constant rate RGW ($cm.day^{-1}$) until it reaches a depth RDM (cm), which is the minimum value of (1) the crop specific maximum rooting depth and (2) the maximum rootable depth of the soil.

Initial soil water contents are user-defined, e.g. θ_{2d} as discussed in chapter 6, or to the final value under the previous crop, in the case of crop rotations or ratoon cane.

Distribution of infiltrating rainwater

The model uses a simple instantaneous "tipping bucket" representation of water percolation through the soil. Infiltrating (rain) water starts filling the upper compartment to a water content of θ_{2d}. Then percolation to the underlying compartment begins, until this compartment is filled to a water content of θ_{2d} etc... Errors incurred in this simple procedure are presumably small on strongly weathered soils of this study, because the soils are very permeable and there is no groundwater influence. Recall that it was concluded in chapter 6 that the field capacity concept is acceptable in water balance studies of these soils with small percolation losses after 2 days after field saturation.

Transpiration and water withdrawal by roots

The maximum transpiration rate (TR_m, $cm.day^{-1}$), i.e. the transpiration rate when water supply from the soil is adequate, is calculated as in PS123 (see table 10.1).

The assessment of the effect of soil water status on transpiration is based on the concepts proposed in chapter 9 (section 9.6), extended with a simple algorithm, based on PS123, to account for insufficient aeration. It is assumed that, from an initially wet soil, a fraction p_{soil} of total available soil water can be removed before the actual transpiration rate (TR_a, $cm.day^{-1}$) drops below TR_m; after which TR_a/TR_m decreases linearly with the amount of available water left in the soil. The fraction p_{soil} is distributed over the rooted soil depth as indicated in figure 9.9, in analogy with the soil water uptake distribution reported by Gardner (1983), assigning to each compartment i a specific soil water depletion fraction p_i.

Water withdrawal from the soil during one time interval is accomplished in N_i+1 steps, where N_i is the number of rooted compartments. For each step j, and each rooted compartment i, the model determines the "relative available water content", $\Theta_{r,i,j}$:

$$\Theta_{r,i,j} = (\theta_{i,j} - \theta_{-1.5Mpa}) / (\theta_{2d} - \theta_{-1.5Mpa}) \quad \text{(A2.1)}$$

where $\theta_{i,j}$ is the water content of compartment *i*, just before step *j*.

"Drought limited relative water availability" $f_{dry,i,j}$ (-), is calculated for each compartment as:

$$f_{dry,i,j} = \Theta_{r,i,j} / (1-p_i) \quad \text{(A2.2)}$$

"Aeration limited relative water availability" $f_{wet,,i,j}$ (-), is calculated for each compartment as:

$$f_{wet,,i,j} = U_{r,wet,min} + (A_{i,j}/A_{cr}) * (1.0 - U_{r,wet,min}) \quad \text{(A2.3)}$$

conditioned by $0 \leq f_{wet,,i,j} \leq 1$

where,

A_{cr} is the volumetric air content of the soil ($cm^3.cm^{-3}$; A_{cr}>0.) above which water uptake is not restricted by insufficient aeration;

$A_{i,j}$ is the actual volumetric soil air content ($cm^3.cm^{-3}$) in compartment *i* in step *j*;

$U_{r,wet,min}$ is a dimensionless parameter ($U_{r,wet,min} \leq 1.$).

Figure A2.1 shows relationships between $A_{i,j}$ and $f_{wet,,i,j}$ for A_{cr} = 0.08 $cm^3.cm^{-3}$ and several values of $U_{r,wet,min}$.

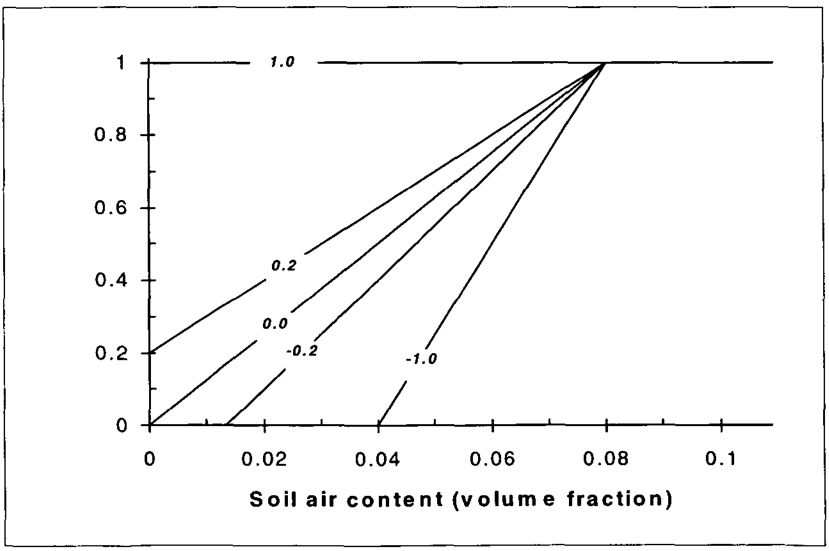

Figure A2.1 Relative aeration limited soil water uptake ($f_{wet,i,j}$) as a function of air content of soil compartment *i* in step *j*, for A_{cr} = 0.08 $cm^3.cm^{-3}$ and values of parameter $U_{r,wet,min}$ of -1.0, -0.2, 0.0, 0.2 and 1.0

The minimum value of $f_{dry,i,j}$ and $f_{wet,i,j}$ is the final "water availability index" $f_{r,i,j}$.

Water withdrawal $U_{imax,j}$ (cm.day^{-1}) from compartment i_{max}, i.e the compartment with largest $f_{r,i,j}$ is calculated as:

$$U_{imax,j} = MIN(1., f_{r,imax,j}) * TR_m \qquad (A2.4)$$

Before proceeding with step j+1, $\theta_{imax,}$ is adjusted:

$$\theta^*_{imax,j} = \theta_{imax,j} - U_{imax,j} * \Delta t * (N_i+1)^{-1} * D_i^{-1} \qquad (A2.5)$$

where,

$\theta^*_{imax,j}$ is the water content of compartment i_{max}, at the end of step j (cm^3.cm^{-3});

D_i, the thickness of compartment i (cm)

Δt the time interval (days)

To avoid excessive water uptake from a small compartment, a maximum limit of 0.02 cm^3.cm^{-3}.day^{-1} is imposed on water withdrawal by roots (c.f. Hoogland et al., 1981); and $\theta_{i,j}$ is not allowed to drop below $\theta_{-1.5MPa}$ as a consequence of root water uptake.

The model offers two options to calculate TR_a from this procedure:

1) TR_a is calculated after completion of step N+1. In this representation, TR_a is determined by the water content of the soil compartment(s) in which water is most readily available.

2) Alternatively, TR_a is calculated as

$$TR_a = TR_m * MIN(1., f_{r,soil}) \qquad (A2.6)$$

where $f_{r,soil}$ is the "relative water availability" calculated by applying equations A2.1, A2.2 and A2.3 to p_{soil} and soil water contents averaged over the rooted part of the soil. Equations A2.1 to A2.5 are still used at compartment level, but the "loop" is left when cumulative water extraction during the time interval reaches TR_a (equation A2.6).

Options 1 and 2 give identical results when soil water is initially homogeneously distributed, but great differences exist when wet and dry layers occur immediately above or below each other.

The question of appropriate values for the soil water depletion fraction (p_{soil}) also remains unsettled (see chapter 8). The model offers options, to choose a fixed crop specific value or to adopt the method of Doorenbos & Kassam (1979) or that of Allan et al. (1998) as discussed in chapters 8 and 9. The model also offers the option to calculate $\Theta_{r,i,j}$ as a logistic function of soil water content rather than according to the linear relation of equation A2.1.

CURRICULUM VITAE

Maurits van den Berg werd geboren op 3 maart 1960 te Lexmond. In juni 1978 behaalde hij het diploma Atheneum B aan het Christelijk Lyceum te Gouda. Van september 1978 tot januari 1986 studeerde hij aan de Landbouwhogeschool te Wageningen (tegenwoordig Wageningen Universiteit), met als hoofdvak Tropische Bodemkunde. Gedurende deze studie vervulde hij een 8 maanden durende stageopdracht betreffende bodemgeschiktheid in het gebied rond Araras waarbij hij verbonden was aan het Instituto Agronômico te Campinas (SP, Brazilië). Vervolgens verrichtte hij een jaar onderzoek naar bodempatronen in de overstromingsvlakte van de Rio Ribeira (SP), bij hetzelfde onderzoeksinstituut.

In februari 1986 trad hij als toegevoegd docent in dienst bij de Landbouwhogeschool te Wageningen en in februari 1987 als onderzoeker in opleiding bij WOTRO/NWO met als voornaamste standplaatsen Campinas, Assis en Passo Fundo (Brazilië) voor de uitvoering van het onderzoek dat uiteindelijk leidde tot dit proefschrift.

In september 1991 trad hij als wetenschappelijk medewerker in dienst bij het International Soil Reference and Information Centre (ISRIC) te Wageningen in het kader van het UNEP project Reinforcement of Regional Capabilities for Soil Degradation Assessment. In december 1992 werd hij als Suppletie Deskundige gecontracteerd door het Directoraat Generaal Internationale Samenwerking (DGIS) voor de functie van docent Bodemkunde aan de Landbouwfaculteit van de Eduardo Mondlane Universiteit te Maputo, Mozambique. Behalve het verzorgen van onderwijs verrichte - en begeleide - hij daar onderzoek op het gebied van o.a. land degradatie, bodemvruchtbaarheidszonering en bodemkennis bij rurale bevolkingsgroepen. Sinds mei 2000 is hij als medewerker ICT ontwikkeling verbonden aan het Departement Omgevingswetenschappen van Wageningen Universiteit.

PUBLICATIONS

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