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COVER CROPPING IN WATER LIMITED ENVIRONMENTS

A FIELD AND MODELLING STUDY OF HYDROLOGICAL AND SOIL STRUCTURAL EFFECTS OF COVER CROPS AND THEIR IMPACT ON THE WATER BALANCE

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Acknowledgement

From the point of view of the author of the present thesis, creation of knowledge in general, and modern science in particular is a collective process. This is valid even more in case of newcomers who want to assimilate as much existing knowledge as possible in the course of their first self-made contributions. Such a vision may be in contradiction with a trend in current society to substitute creative productivity by competition driven profitability. To the fortune of the author, he still could find during the four years of work on this thesis a scientific environment of free creativity and collegiality. In this sense a large number of colleagues and friends contributed to this work and should be mentioned here.

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Preface

The present thesis is the result of a two years' field study on the water balance of cover crops in comparison with a bare soil under the semi-arid climatic conditions of the pannonic region of Eastern Austria. The idea for this project was born after several years of research dealing with different aspects of cover cropping at the Agricultural College Hollabrunn in cooperation with the Institute of Agronomy and Plant Breeding.

In the scientific literature still few detailed data and rather contradictory results on cover crop effects on the soil water dynamics are found. This complicates a precise answer to farmers' concern on cover crop induced soil water depletion and the related risk for yield losses in water limited environments. Results from lysimeter studies have shown reduced deep percolation under cover crops and suggested around 30 % higher evaporative losses to the atmosphere.

A main objective of our field experiment, started in August 2004, was to improve the knowledge on cover crop-soil-water relations by providing comprehensive data on both the cover crop plant material, particularly in relation to root parameters which are hardly dealt with in literature, as well as soil hydrological and physical changes in cover cropped fields. These data should be acquired under conditions that allow a reliable extrapolation to the farmers' field. Therefore we decided to use a concept of a hydrological field measurement site sometimes referred to as a "virtual lysimeter" where measurements are done in the undisturbed soil and the use of standard machinery for common tillage operations is possible.

A question frequently arising in agricultural and environmental sciences with high relevance for practical agriculture is how to manage the extremely complex and dynamic soil system and how soil physical properties could be stabilized or even improved by agro-environmental instruments like cover cropping. This has become even more relevant in the frame of climatic change effects with an increasing tendency to weather extremes in Central Europe in order to guarantee an optimum water supply to the crop plants.

Therefore an additional interest of our study, besides the determination of the components of the water balance under cover crops, were plant-soil interactions in relation to soil structure formation and stabilization and its consequences on hydraulic properties of the site.

The first results achieved in this field study and the feedbacks between our empirical observations and their analysis with simulation models presented in this thesis, will give some indications which processes of the water dynamics are mainly subjected to cover crop influences, which plant traits are essential for these plant effects and how sustainable agricultural water management could take advantage of such interactions between plant and soil.

Abstract

Cover cropping is a commonly used agro-environmental tool promoted by European and national authorities for soil and groundwater protection. Still there is concern that cover crops may induce water storage depletion in semi-arid environments with negative effects on cash crop yield. The objective of this study was to assess the risk of soil water depletion by analysing the effects of cover crops on soil structural and hydrological processes, in order to improve cover crop management for water limited conditions.

Cover crop impacts on the water balance and on soil hydraulic properties were investigated over two years in a field experiment in the semi-arid region of Eastern Austria. The experiment was equipped with a hydrological field measurement site. Cover crop plants (phacelia, hairy vetch, rye, mustard) were characterized in terms of aboveground and root biomass, soil cover and rooting patterns. The infiltration properties in the structure related macropore space were measured with a tension infiltrometer. An integrated analysis of evapotranspiration and soil water dynamics was done using the FAO Dual Crop Coefficient method and the hydrological model HYDRUS 1D.

Mustard was most stable in soil cover and aboveground biomass growth under dry conditions with an intense vertical and lateral root system. Vetch had a low root length density, but a homogeneous depth distribution of roots that could sustain a high biomass growth even under dry conditions. Phacelia was susceptible to drought in autumn during the main growing period. Its root system was characterized by a high root density near the shoot base with a fast decrease in both, the vertical and horizontal direction. Rye did not exceed 60 % soil cover even under optimum conditions and had the lowest aboveground biomass, while it provided a high root biomass and dense rooting of the soil.

Cover crops showed a higher cumulative evapotranspiration under dry conditions during their main growing period in autumn compared to fallow. Scenario analysis revealed maximum additional evaporative losses of 27.6 %. Plant transpiration accounted for only 17.6 % to 52.6 % of total evapotranspiration. The additional water losses by root water uptake of the cover crops from deeper soil layers induced differences in water storage of 7.1 % compared to a bare soil and were reduced over winter to 2.8 %. In the upper soil layers there were no water content differences in spring and no statistically significant yield losses were found for the subsequent cash crops.

The management effect of cover crops on hydraulic conductivity in the macropore range was displaced by other structure forming factors inducing a high temporal and special variability. The high conductivity near saturation of a bare soil was attributed to the contribution of shrinking cracks which, however, revealed to be less stable over winter. A stabilization of macropores by cover crops and a related higher increase of hydraulic conductivity over winter could be shown.

From the results of our study we concluded that (i) the broad introduction of cover cropping is feasible in the semi-arid region of Central Europe, where potential evaporative losses from the cover crops stands are limited by the low saturation vapour deficit of the atmosphere in autumn, without higher risk of yield losses due to water storage depletion, (ii) a water efficient cover crop management must focus on the reduction of unproductive losses by soil evaporation in late summer by a fast canopy cover and (iii) short term effects of cover crops on soil structure and the related hydraulic properties in the macropore range can be expected for structure stabilization rather than formation.

Based on these results further research should focus on field methods and modelling approaches to quantify plant-soil interaction effects on the dynamics of soil hydraulic properties in order to improve decision support in agricultural soil and water management.

Keywords: Cover crops, water balance, evapotranspiration, infiltration, soil structure, modelling

Kurzfassung

Zwischenfruchtbau ist eine verbreitete und durch europäische und nationale Agrarumweltprogramme geförderte Maßnahme zum Boden- und Grundwasserschutz. In Trockengebieten wird jedoch eine Ausschöpfung des Bodenwasservorrats mit negativen Auswirkungen auf die Hauptfruchterträge befürchtet. Zur Analyse dieses Risikos wurden Veränderungen der Bodenwasser- und Strukturdynamik unter einer Pflanzendecke untersucht, um ein verbessertes Managements für wasserlimitierte Standorte zu definieren.

Zwischenfruchteffekte auf die Wasserbilanz und hydraulischen Bodeneigenschaften wurden über zwei Jahr im Rahmen eines Feldversuches in der semi-ariden Region Ostösterreichs untersucht. Der Feldversuch wurde mit einer hydrologischen Messstelle ausgestattet, oberirdische Biomasse, Bodenbedeckung und Wurzelparameter der Zwischenfrüchte (Phacelia, Winterwicke, Roggen, Senf) wurden charakterisiert und die Infiltration im Makroporenbereich mittels Tensionsinfiltrometer gemessen. Die Analyse der Zwischenfruchteinflüsse auf Evapotranspiration und Bodenwasserdynamik erfolgte mit der FAO Pflanzen-Koeffizienten-Methode sowie dem hydrologischen Modell HYDRUS 1D.

Biomassebildung und Bodenbedeckung von Senf, mit starker Hauptwurzel und intensiver Seitenwurzelbildung, erwiesen sich am stabilsten gegenüber Trockenheit. Wicke zeigte eine geringe Wurzeldichte, jedoch eine homogene Tiefenverteilung, die auch unter trockenen Bedingungen eine hohe Biomassebildung erlaubte. Phacelia reagierte sensitiv auf Trockenheit zur Hauptwachstumszeit im Herbst. Ihr Wurzelsystem war nahe der Sprossbasis konzentriert und nahm in vertikale und horizontale Richtung rasch ab. Roggen erreichte auch unter günstigen Bedingungen weniger als 60 % Bodenabdeckung bei geringer oberirdischer Biomasse. Die Durchwurzelungsintensität des Bodens war jedoch sehr hoch.

Die Zwischenfrüchte zeigten bei herbstlicher Trockenheit erhöhte Verdunstungsverluste im Vergleich zu Brache. Über Szenarioanalyse wurde ein höherer Wasserverlust von maximal 27,6 % ermittelt. Die Transpiration machte nur zwischen 17,6 % und 52,6 % der gesamten Evapotranspiration aus. Der höhere Wasserentzug aus tieferen Schichten führte im Herbst zu einer um 7,1 % geringeren Wassermenge im Profil. Diese Differenz reduzierte sich über Winter auf 2,8 %. In den obersten Bodenschichten konnten im Frühjahr keine Wasseranteilsunterschiede festgestellt werden. Die Ertragsdifferenzen zwischen den Hauptfrüchten waren in beiden Jahren statistisch nicht signifikant.

Der Einfluss der Zwischenfrüchte auf die Höhe der hydraulische Leitfähigkeit im Makroporenbereich wurde durch andere strukturbildende Faktoren überlagert, die eine hohe räumliche und zeitliche Variabilität bedingten. Die hohe Leitfähigkeit der Brache nahe der Sättigung wurde auf Schrumpfrisse zurückgeführt, die jedoch über Winter geringe Stabilität zeigten. Die höhere relative Zunahme der Leitfähigkeit über Winter unter den Zwischenfrüchten weist auf das Potential zur Struktur-Stabilisierung im Bereich der Makroporen hin.

Die Ergebnissen zeigen, dass (i) eine breite Nutzung von Zwischenfrüchten in semiariden Gebieten Mitteleuropas ohne überhöhtes Risiko von Ertragsverlusten der Hauptfrucht möglich ist, da der Wasserentzug entwickelter Zwischenfruchtbestände durch das geringe herbstliche Sättigungsdefizit der Atmosphäre limitiert ist. (ii) Ein wassereffizientes Management der Zwischenfrucht muss auf die Verminderung unproduktiver Bodenverdunstung im Spätsommer durch eine rasche Bodenbedeckung abzielen. (iii) Kurzfristige Wirkungen der Begrünung auf Bodenstruktur und hydraulischen Eigenschaften im Makroporenbereich zeigen sich als Struktur- und Porenstabilisierung, weniger jedoch als erhöhte Neubildung.

Forschungsbedarf ergibt sich in der Weiterentwicklung von Feldmethoden und Ansätzen zur dynamischen Modellierung hydraulischer Bodeneigenschaften im Strukturbereich, die zur Verbesserung von Boden- und Wassermanagement in der Landwirtschaft beitragen können.

Schlüsselworte: Zwischenfrüchte, Wasserbilanz, Evapotranspiration, Infiltration, Bodenstruktur, Modellierung

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1 Introduction

Modern agriculture can be characterized by its multifunctionality where farmers' traditional task of food production is inserted into a framework of public demands concerning environmental care and landscape conservation. This requires high flexibility with respect to the design of sustainable crop rotations and the inclusion of new agro-environmental management instruments to comply with the growing number of national and European regulations. Sustainability in this sense is more than the conservation of natural resources as the essential and hardly renewable bases for food production. It needs continuous adaptation, change and improvement of a variety of agricultural and environmental measures to the ambient conditions evolving in terms of both, the political as well as the environmental framework itself when taking into account global change effects.

Conservation, stabilization and eventually improvement of the physical properties of the soil are a fundamental concern for a sustainable production strategy as soil fertility and productivity depend on the functionality of the processes which determine these soil quality attributes. The potential impacts of climate change and the related challenges for management of the water cycle will make soil physics a central discipline in life sciences and research for sustainability. While soil and environmental physics together with plant biology provide the bases for describing, quantifying and understanding the processes underlying empirical observations, agronomy focuses on measures to influence such processes in benefit of the farmer and society. Thus an integrated scientific approach between soil physics, plant biology and agronomy is essential to provide the basic knowledge to define agricultural systems that allow a sound interaction between the needs of agricultural food production and the conservation of natural resources in a changing environment.

In 1951 a pioneer of soil conservation, Franz Sekera, defined permanent plant cover as a key factor in soil fertility management. Plants are the main catalyst – mediated by soil fauna – for transforming the products of weathering into the living system of soil. This first scientific approach to the introduction of cover plants into the crop rotation during the fallow period between two cash crops relied on an ancient agricultural tradition of green manuring dating back to written testimonies until the Roman Empire.

When the vulnerability of groundwater to diffuse source of agricultural contaminants, mainly nitrate, was revealed, Sekera's strategy of soil structure and fertility management by green manuring turned out to be also a key tool for groundwater protection. Consequently cover cropping became a wide spread measure within European agro-environmental programmes based on EC Directive 1257/99.

Cover cropping since then has proved its efficiency in groundwater protection and is widely recognized as part of sustainable crop rotations among farmers. However in arid and semi-arid regions the extension of cover cropping is facing concerns on soil water storage depletion and related yield losses. If research for sustainability proclaims to contribute to long term productivity, it will have to deal with this aspect of a permanent plant cover of the soil, even more as water is likely becoming a scarce resource in large areas of Europe in the course of global change.

Taking into account the complexity of fluxes in the soil-plant-atmosphere continuum, it is likely that the answers from science will be given with a lot of constraints and some quibbling. This however is an expression of real world variability and the multitude of potential cover crop effects on the water resources in different soils, climates and years. Research on plant-soil-water relations cannot be expected to find simple linear cause-effect schemes that allow a precise prognosis on every year's yield effect of a cover crop on a single farmer's field. Results of studies dealing with cover crop effect on the water dynamics will rather highlight the main components of the water balance being influenced and the range of the potential impacts trying to understand the underlying processes and their modification by this management instrument. Maybe this will neither satisfy the farmer nor the policy makers. We still consider that the general objective of this work, i.e. human management of complex natural systems, may lead to some answers that are beyond the description of single year-single field effects and provide (i) a better assessment of the risk scenario farmers may face due to cover crop water extraction in semi-arid environments and (ii) some bases and indications how to adapt management for such water limited sites.

The present work is based on the evaluation of first results from a field study started in August 2004 in the pannonic region of Eastern Austria being equipped since August 2005 with a variety of modern soil water measurement devices to provide the empirical data base for the above mentioned research question. A variety of additional parameters has been determined by a range of field and laboratory methods from soil physics and applied plant sciences. The following work will present these measurement results and analyse the related processes using statistical, hydrological and empirical models. This combination of field observation, statistics and modelling should help to extract some general concepts and ideas from our findings in order to contribute to the scientific assistance in optimizing the agro-environmental benefits of cover cropping.

2 Objectives, hypotheses and structure of the study

The objective of the present study is sustainable agricultural water management in the framework of a central agro-environmental measure implemented by the EC Directive 1257/99. Its object of investigation are cover crops integrated in the crop rotation to protect the soil during autumn and winter, avoid losses of nitrate to the groundwater and promote the organic matter input to improve the humus balance. The practical agricultural background of the investigation are concerns on the soil water storage depletion due to cover cropping by farmers in semi-arid environments where precipitation input into the soil during autumn and winter is considered essential for the water requirements of subsequent cash crops. The questions to be answered from the point of view of agricultural praxis are:

(i) To what extend will cover crops induce water storage depletion and reduce the yield of following cash crops?

(ii) What might be the best management practices in cover cropping to reduce the risk of yield losses without limiting the environmental benefits of a cover crop?

(iii) Which cover crop species are adequate for the semi-arid climate in terms of water conservation?

In the field of natural sciences, this work is situated at the linkage between applied plant sciences and soil physics, concretely in topics related to plant-soil interactions in the root zone and in particular their effects on soil hydraulic properties and the water fluxes in the soil-plant-atmosphere continuum. The main focus of this work will be on two aspects of cover crop effects on the components of the water balance and their consequences for soil water storage during the fallow period between the main crops, being

(i) the quantitative importance of soil evaporation and plant transpiration for the overall gaseous water losses to the atmosphere under a plant cover during autumn and winter compared to bare soil,

(ii) cover crop effects on the structural (macro)pore space in relation to the natural spatial and temporal variability of soil structure and the possibilities of managing the infiltration process by means of cover plants.

An integrated view on the quantitative changes of the water balance components will be provided by a model based analysis of the water fluxes in the cover crop system compared to bare soil.

Based on a review of the current knowledge on plant-soil interactions and their effects on the hydraulic properties of the soil with a particular attention to studies related to cover crop impacts, we define the following hypotheses for our research:

HYPOTHESIS 1: EVAPOTRANSPIRATION

The reduction of soil evaporation by a plant cover leads to a redistribution of the evaporative water losses towards plant transpiration. This results in low differences in total evapotranspiration and a minor risk for depletion of the profile water content in a cover cropped field compared to a bare soil.

HYPOTHESIS 2: INFILTRATION

Cover crop plants improve the infiltration properties of the soil and induce a higher hydraulic conductivity in the macro-pore space due to the protection of soil structure at the soil surface by canopy coverage, the induction of biopores in the root zone and the promotion as well as stabilization of pores by organic matter input. Cover cropping therefore is a management instrument to improve the infiltration properties and reduce runoff and soil erosion in a sloping field.

HYPOTHESIS 3: WATER STORAGE DEPLETION

A potentially higher water extraction during the cover crop vegetation period will be equilibrated over winter due to compensating mechanisms like enhanced infiltration, reduced soil evaporation and deep drainage losses. The change in profile water storage even under a cover crop with high water demand therefore will not differ substantially from a bare soil in terms of water availability for the subsequent cash crop in spring.

The present study consists of four main chapters (chapters 5 to 8) with their structure oriented on guidelines for scientific papers. Thus each chapter dealing with a specific question related to the hypotheses formulated above can be read on its own. A general review of literature on plant-soil interactions and their effects on soil structure and water dynamics is given in *Chapter 3*. In order to avoid repetitions in relation to the description of the general setup of the field experiment and the site characteristics of the experimental field in the following chapters, this part of description of the material used is presented separately *(Chapter 4)*, while specific aspects of the site characterization and methods applied in each thematic focus are dealt with in the single chapters. *Chapter 5* is dedicated to the detailed description of the cover crop plant material, particularly ground cover and root characteristics, which are related in the following chapters to impacts on the soil water dynamics and hydraulic properties, i.e. evapotranspiration *(Chapter 6)*, infiltration and hydraulic conductivity *(Chapter 7)*. An integrated view of potential differences in the soil water status of a cover crop system compared to a bare soil is given in *Chapter 8* based on a modelling study.

Final remarks related to our initial hypotheses and based on the conclusions of the single chapters as well as an outlook on further research questions arising from our results will be discussed in *Chapter 9*.

3 State of science on hydraulic effects of plant-soil interactions

Soil structure is recognized as a fundamental soil quality indicator and has to be considered in sustainable soil management strategies (European Commission, 2002). It is widely recognized that plants significantly influence soil structure and soil water dynamics (Angers and Caron, 1998). However there are few advances in modelling the effects of plant and root induced soil structural changes on soil hydraulic properties. In most models plants still are reduced to a “sink term” extracting water out of the system, while their physical, biological or biochemical influences in the root zone on the soil pore system itself are neglected. However, to assess the influence of cropping systems or agro-environmental measures over time on the hydraulic properties of the soil, mainly in the dynamic structural range, a quantitative description of soil-plant interactions would be required (Green et al., 2003; Horn and Smucker, 2005).

Empirical research has provided huge evidence for the close relations of plant roots, plant carbon input and soil structure. The concept of aggregate hierarchy by Tisdall and Oades (1982) describes soil structure formation, stabilization and breakdown as a function of the dynamics of organic binding agents. Soil aggregate size distribution as a result of this process has been used to predict the pore size distribution and corresponding soil hydraulic functions (Nimmo, 1999). Temporal dynamics of aggregate formation, stabilization and breakdown as a result of plant organic matter input and turnover therefore provide a link for understanding and quantitatively describing changes of soil hydraulic properties.

An important agricultural management strategy to improve soil structure by permanent soil cover and high organic inputs is the use of cover crops (Cherr et al., 2006). Concerning the water balance, possible increases of soil infiltrability and water holding capacity (Folorunso et al., 1992; Joyce et al., 2002) have to be considered at the same time as the problem of soil water depletion for the succeeding main crops, mainly in semi-arid and arid environments (Mitchell et al., 1999; Islam et al., 2006).

The following section provides a short literature review on the general topic of hydraulic effects of plant-soil interactions and scientific contributions from different fields of agricultural and soil research. This introduction should highlight the wide range of processes in the rhizosphere to be considered in the analysis of a cover crop agro-ecosystem although only some of them could be investigated in the present research work.

3.1 Soil structure and soil hydraulic properties

Dexter (1988) defined soil structure as the spatial heterogeneity of the different components or properties of soil. With respect to soil hydraulics, soil structure is related to the pathways and voids formed between structural units of the solid phase (particles and aggregates). Both fundamental relations for soil water flow, the retention and hydraulic conductivity functions, are influenced by soil structure mainly in the saturated and near-saturated range of about 0 to -30 kPa (Cresswell et al., 1992). The pore size distribution of structured soils often shows a bimodal or even multimodal form with local maxima in the structural (inter-aggregate) and matrix (intra-aggregate) domain of water flow (Kutílek, 2004).

Several approaches to predict soil hydraulic properties from readily available soil data consider soil structural descriptors like bulk density or penetration resistance (e.g. Pachepsky et al., 1998; Pachepsky and Rawls, 2003). Nimmo (1999) presented a semi-empirical approach to predict separate retention and conductivity functions for the structural range based on the aggregate size distribution.

Distinct hydraulic functions for the matrix and structural domain, derived either from measured data or using pedotransfer functions, are used in dual-porosity models mainly to predict water, solute and particle transport by preferential flow. In a review, Šimůnek et al.

(2003) concluded that the two major problems of modelling a separated structural domain are the increasing number of parameters and the temporal changes due to physical, biological and human influence that are not considered in existing models.

3.2 Aggregate size and pore size

The relation between the aggregate size distribution and the pore size distribution has been investigated by several authors (e.g. Wu et al., 1990; Guber et al., 2003; Li et al., 2004). Rasse et al. (2000) showed a significant increase in saturated hydraulic conductivity and macroporosity due to a higher aggregate mean weight diameter. Lebron et al. (2002) found a significant correlation between median aggregate size and pore size determined by scanning electron micrographs and image analysis.

There have been critical remarks made on aggregate based soil structure quantification as it implies artificial disruption of the natural arrangement of soil particles and voids between them (Diaz-Zorita et al., 2002). However, modern physical fractionation techniques allow a more accurate determination of the aggregate size distribution using known amounts of energy for a gentle disruption of the natural arrangement of particles by ultrasonic energy along naturally occurring failure zones (e.g. Christensen, 2001; Mentler et al., 2004). In order to assess plant influences on soil structure dynamics, the aggregate concept provides a useful link to the biological and biochemical mechanisms of structure formation and stabilization (Kay, 1998; Six et al., 2004).

3.3 Temporal dynamics of soil structure and hydraulic properties

Knowledge about spatial and temporal variability of soil properties is fundamental to accurately describe soil processes like water infiltration and storage (van Es et al., 1999). Changes in soil structural features occur on different temporal scales. Land use changes induce a long term adaptation of soil properties (e.g. Fuentes et al., 2004). Over the vegetation period changes in soil structure and soil hydraulic properties are related to weather conditions (e.g. Angers, 1998; Klik et al., 1999; Rousseva et al., 2002), plant and root growth (e.g. Strizaker et al., 1996; Angers and Caron, 1998; Rasse and Smucker, 1998), organic carbon and soil (micro)biological dynamics (e.g. Plante et al., 2002) and soil management (e.g. Angulo-Jaramillo et al., 1997; Snyder et al., 2000; Leij et al., 2002).

Concerning soil hydraulic properties in relation to soil structure parameters, Green et al. (2003) reviewed existing modelling approaches to describe the variability in time of water retention and hydraulic conductivity due to agricultural management practices. Models frequently rely on empirically measured coefficients of change integrated into a pedotransfer function or directly in the hydraulic property equation. Most quantitative approaches have been developed to describe changes related to different tillage systems (Williams et al., 1984; Ahuja et al., 1998; Xu and Mermoud, 2003). Or et al. (2000) were the first in developing a pore scale model for temporal changes of soil hydraulic properties considering the evolution in total porosity, mean pore radius and variance for a log-normal pore size distribution. The approach is promising as it directly focuses on the pore size distribution which is the determinant for the hydraulic properties of a soil and it is open to be linked to a mechanistic modelling of the coefficients describing temporal changes of the single pore size classes as shown by Leij et al. (2002).

3.4 Plant and organic matter influences on soil structure

The decisive influence of plants on soil structure and soil hydraulic properties has been demonstrated by numerous research works (e.g. Angers and Caron, 1998; Baldock, 2002; Gregory, 2006). According to Tisdall and Oades (1982), soil structure is related to the dynamics of biological and biochemical binding agents between the primary particles resulting in differently sized aggregates.

Jastrow et al. (1998), Rasse et al. (2000) and Feeney et al. (2004) among others showed the mechanism of root entanglement in the formation and stabilization of macroaggregates, often linked to the effect of mycorrhizal fungi associated with the plant roots. Plant roots not only affect aggregation of the soil particles, but also show direct influence on the pore system of the rhizosphere soil through local compression, crack formation via wetting-drying cycles and biopore formation (e.g. Dexter, 1987; Mitchell et al., 1995; Young, 1998; Whalley et al., 2005).

The application of modern analytical methods like FT-IR spectroscopy improved the characterization of organic structures and their changes in the decomposition process (e.g. Haberhauer and Gerzabek, 1999; Ellerbrock et al. 1999). Golchin et al. (1998) showed chemical changes in organic matter associated with particulate organic matter decomposition on the aggregate level. Monreal et al. (1995) determined linear correlations between distinct organic structures and different aggregate size classes. Macroaggregates were highly correlated with lignin dimers, sterols and alkylaromatics. Several authors showed that the labile organic carbon fraction is a particularly susceptible indicator of changes in soil management (Shepherd et al., 2002; Jinbo et al, 2006).

For evaluating relations between biological and organic input parameters and soil structural characteristics, Miller and Jastrow (1990) and Rilling et al. (2002) developed a path model for water stable macroaggregates as influenced by root parameters, mycorrhiza, organic carbon and microbial biomass. De Gryze et al. (2005a,b) presented a study showing the potential for a mechanistic description of the aggregate dynamics based on the turn-over kinetics of organic carbon.

3.5 Cover crops and water balance

Several agro-environmental programmes promote cover crop use to prevent leaching of soil nutrients, and to reduce runoff and soil erosion. Permanent soil cover and high organic inputs of cover crops contribute to a sustainable management of soil fertility (Ruan et al., 2001, Roldán et al., 2003, Guangwei et al., 2006).

In semi-arid and arid environments cover crops can deplete the soil water availability for the following cash crops due to their transpiration demands (Mitchell et al., 1999; Salako and Tian, 2003; Islam et al., 2005; Nielsen and Vigil, 2005). However cover crops not only influence the water balance by water uptake. Colla et al. (2000) demonstrated that cover crops increased both the water holding capacity and the soil permeability. Folorunso et al. (1992), Martens and Frankenberger (1992) and Joyce et al. (2002) found improved rainfall infiltration in cover cropped plots compared to a fallow rotation. In the study of Liu et al. (2005) an increased aggregate mean weight diameter was found for nonleguminous winter cover crops, highly correlated to the quantity of polysaccharides in the soil. Kabir and Koide (2002) found higher aggregate stability under oat and rye used as cover crops which was related to their mycorrhizal colonisation by the authors. Williams and Weil (2004) showed that cover crops could be an effective way to alleviate soil compaction due to root biopores being used by the following soybean crop to penetrate the soil.

Although the complex influence of cover crops on the water balance is recognized, there are still few studies combining detailed field measurements with model based analysis to improve the quantitative knowledge on cover crop effects on soil structure and soil water dynamics as a basis to improve our capacity to define a sustainable cover crop management strategy particularly for water limiting environments.

3.6 Literature

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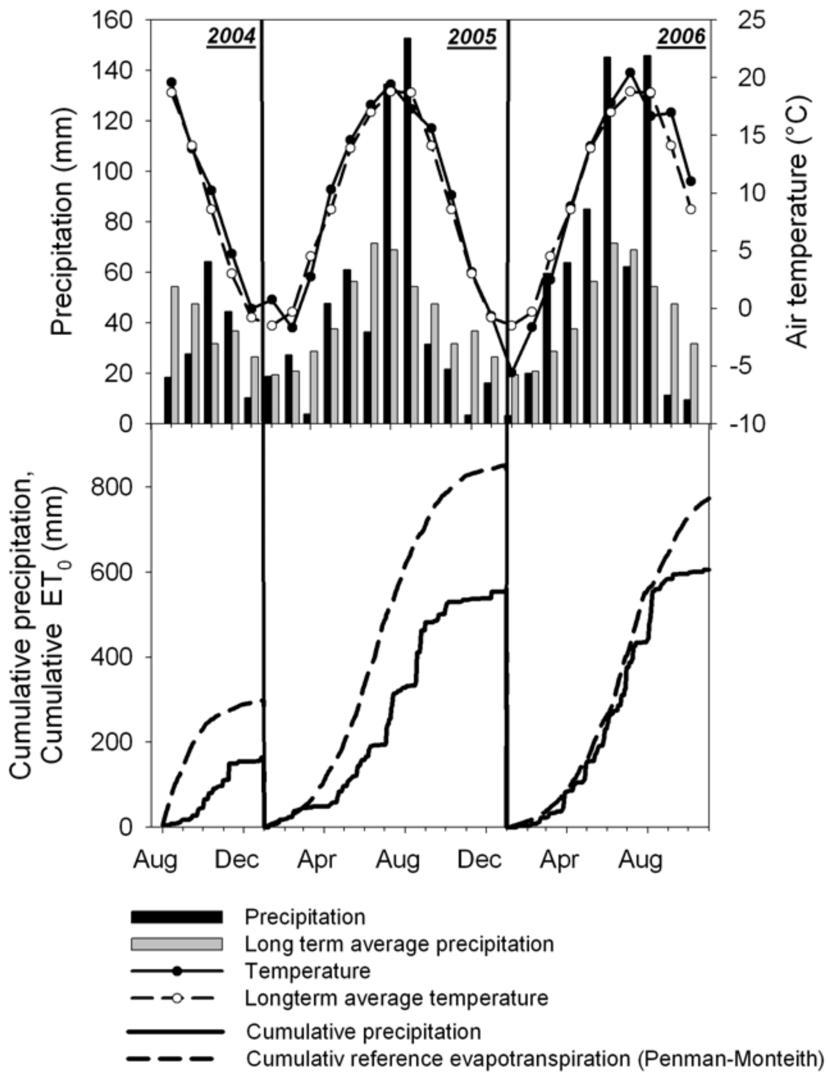
4 Field study material

4.1 Experimental site and setup

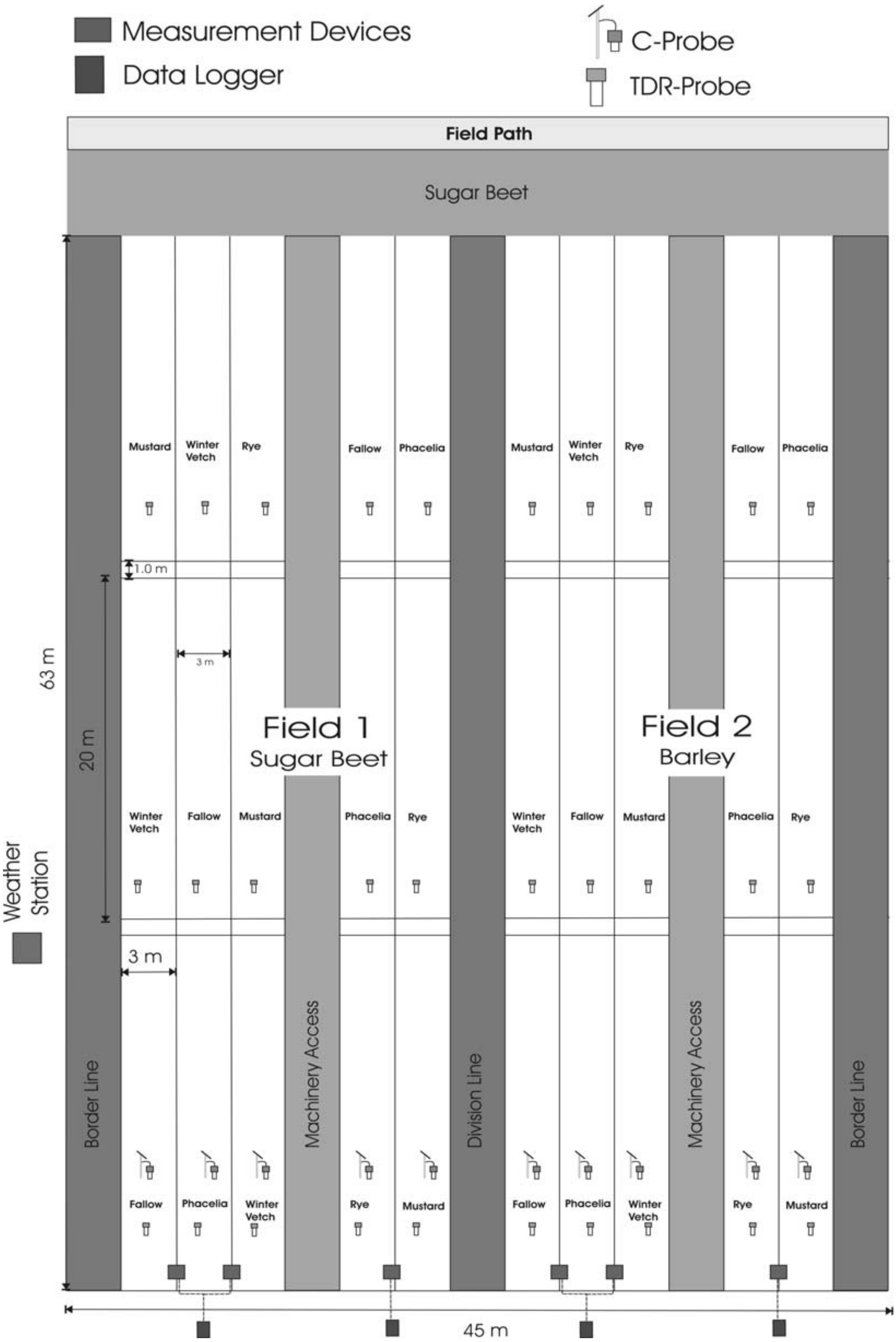
A field experiment was set up in August 2004 in the pannonic region of Eastern Austria in Hollabrunn (48°12'N and 16°34'E). Climatically Hollabrunn is characterized by semi-arid conditions with an average annual precipitation of 491 mm, a mean temperature of 9.1 °C and an average wind speed of 2 to 4 m s^{-1}. These site characteristics result in a climatic water balance deficit up to 300 mm as shown in Fig. 4.1 for the experimental years. The study site can be considered as representative for regions with semi-arid climatic conditions where water is the main growth limiting factor.

Figure 4.1 Climatic site characteristics.



The field experiment consists of four cover crops from different plant families and with different root charactristics. Phacelia (*Phacelia tanacetifolia* Benth., cv. Vetzrouska) is a non-winter hard cover crop from the Hydrophyllaceae family with only slight thickening of the primary root and an extensive fibrous root system in the upper soil (Wyland et al, 1996; Ehlers and Goss 2003). Hairy vetch (*Vicia villosa* L., cv. Beta) is a winter hard legume species with a primary root branching in several lateral roots of similar diameter (Kutschera, 1960). Rye (*Secale cereale* L., cv. Picasso) is also a winter-hard cover crop with the typical fibrous system of seminal and adventitious roots of Poaceae (Kutschera, 1960). Mustard (*Sinapis alba* L., cv. Caralla) is a non-winter hard Brassicaceae species with a strong taproot (Hampl, 1996). Seeding rates were 10 kg ha^{-1} for phacelia, 90 kg ha^{-1} for vetch, 120 kg ha^{-1} for rye and 10 kg ha^{-1} for mustard. Plot size was 60 m^2 resulting in a size of the whole experimental field of about 0.35 ha. Plots were arranged in a randomized complete block design with three replications (Fig. 4.2).

Figure 4.2 Design of the field experiment.



Following the guidelines of the Austrian agro-environmental programme ÖPUL (BMLFUW, 2000) cover crops were sown on 20 August after a shallow tillage operation using a cultivator to a depth of 10 cm and a rotary harrow before drill seeding with a row distance of 15 cm. The crop rotation consists of sugar beet-spring barley-maize-winter wheat. For the yearly evaluation of cover crops, the trial consists of two parallel rotations as listed in Tab. 4.1.

Table 4.1 Crop rotation.

	FIELD 1	FIELD 2
2004/05	*Cover Crop*	*Cover Crop*
	Sugar Beet	**Spring Barley**
2005/06		*Cover Crop*
	Spring Barley	**Maize**
2006/07	*Cover Crop*	**Winter Wheat**
	Maize	*Cover Crop*

4.2 Basic soil characteristics

Tab. 4.2 shows the basic soil properties of the experimental field. Particle size distribution was measured by sieving and sedimentation analysis (ÖNORM, 2002) and converted to the USDA size classes using a loglinear interpolation method presented by Wösten et al. (2001). The depth of the A_h horizon varies between 30 and 60 cm followed by an AC horizon to a depth between 70 and 90 cm. According to the Austrian Soil Survey, the study site is described as a calcareous chernozem on loess with a high water holding capacity and susceptible to surface crusting and erosion (Österreichische Bodenkartierung, 1986).

Table 4.2 Particle size distribution and bulk density.

Parameter measured	Soil Layer				
	0-10 cm	10-20 cm	20-40 cm	40-60 cm	60-90 cm
Sand (%)	32.6	37.4	36.7	39.2	43.8
Silt (%)	51.2	46.2	48.1	46.9	42.4
Clay (%)	16.1	16.3	15.2	13.9	13.8
Textural class (USDA)	siL	L	L	L	L
Bulk density (g cm^{-3})	1.64	1.63	1.53	1.51	1.48

4.3 Literature

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5 Characterization of cover crop ground coverage and rooting patter

Abstract

Cover cropping is a common agro-environmental practice for erosion control and soil structure stabilization. An adequate management of different cover crop species requires a detailed knowledge about their soil surface cover dynamics and rooting systems under variable climatic conditions. Four commonly used cover crops (phacelia, hairy vetch, winter rye and mustard) have been investigated in a field trial located in the semi-arid region of Eastern Austria in relation to soil surface cover and several rooting parameters. The two experimental years varied substantially in rainfall distribution and climatic water balance deficit, allowing an assessment of the crop specific sensitivity to water shortage during different growing stages. Mustard revealed as most stable under the different climatic conditions in soil cover and aboveground biomass growth. The upper soil was penetrated in the vertical direction by a strong tap root branching in a dense system of finer lateral roots. Vetch showed a high sensitivity to water shortage for germination but was less sensitive to a lack of rain during the later growth period. In spite of a low root length density, the homogeneous rooting of the soil and a shift to deeper root density allocation under dry conditions could sustain a high aboveground biomass and a nearly complete soil cover. Phacelia biomass growth and soil cover were susceptible to drought in the main growing period in autumn. Its root system was characterized by a high root density near the shoot base while the spatial pattern of specific root length suggested a limited root biomass allocation to lateral root growth. Rye did not exceed a soil surface cover of 60 % even under optimum conditions and had the lowest aboveground biomass, while it provided a high root biomass and dense rooting of the soil. Based on the measurement data we derived basic canopy coverage growth and root distribution parameters for the cover crops. These parameters showed the accelerated soil cover growth rate and premature wilting of the cover crops as well as a change in root distribution from an exponential towards a linear decrease with depth under dry conditions.

5.1 Introduction

Cover cropping is a widely used practice promoted by European agro-environmental programmes to reduce negative effects of post-harvest fallowing during autumn and winter. Cherr (2006) listed environmental and economic benefits of cover crops as a source of organic matter and nitrogen as well as their use in sustainable weed and pest management. Numerous studies have shown the potential of cover crops to avoid nitrate leaching following a cash crop by reducing water percolation to the groundwater and binding of mobile soil nitrate into the plant biomass (e.g. Wyland et al., 1996; Shepherd and Webb, 1999; Logsodon et al., 2002; Dinnes et al, 2002; Feyereisena et al., 2006). MacRae and Mehuys (1985) drew attention to the potential of cover and green manure crops to improve soil physical properties. Living crops and mulch cover protect the soil surface from the impact of raindrops and can reduce runoff and soil erosion by more than 95 % compared to fallow (e.g. Dabney, 1998; Meyer et al., 1999; Hartwig and Ammon, 2002). Folorunso et al. (1992), Martens and Frankenberger (1992), Ruan et al. (2001) and Joyce et al. (2002) found enhanced water infiltration under cover crop and mulch systems compared to bare soil. The additional input of organic matter contributes to enhance soil biological activity (Mendes et al., 1999; Schutter and Dick, 2002) and the formation and stabilization of soil aggregates (Kabir and Koide, 2002; Liu et al., 2005). Some concern has been expressed related to soil water depletion by cover crops particularly in arid and semi-arid environments where soil water is the limiting factor for crop production (Mitchell et al., 1999; Salako and Tian, 2003; Islam et al., 2005; Nielsen and Vigil, 2005).

A detailed characterization of plant species used as cover crops is required to understand and manage their potential agronomic and environmental benefits. Depending on the environmental function, studies have focused on different traits of cover crop aboveground and root characteristics. Thorup-Kristensen (2001, 2006) drew attention to the importance of cover crop rooting patterns to mitigate nitrate leaching focussing on their maximum rooting depth. When targeting the reduction of soil erosion, improvement of infiltration and stabilization of soil structure, cover crops require a fast development of a closed surface cover and an intense rooting of the upper soil layers where 80 to 90 % of roots are concentrated in temperate ecosystems (Jackson et al., 1996; Angers and Caron, 1998; Goss and Kay, 2005; Gregory, 2006). As environmental constraints, particularly soil moisture availability, can substantially limit potential aboveground and root growth processes (Klepper, 1987), additional knowledge on the sensitivity of different cover crop species to the variability in climatic growing conditions is required for an adequate management strategy.

Several parameters have been used to describe root systems and their interaction with environment (Atkinson, 2000). In water and nutrient uptake studies, root length density and root surface area density have been used for characterizing vertical and horizontal root distribution (Hopmans and Bristow, 2001; Vrugt et al., 2001; Feddes and Raats, 2004). The relation of aboveground to root biomass has been shown to be particularly sensitive to both water and nutrient stress (Rodrigues et al., 1995; Blum, 1996). Also specific root length has been used to identify different assimilate allocation strategies of plants and their reaction to adverse environmental conditions (Vamerali et al., 2003, Kage et al., 2004).

Models for describing growth processes and root distribution with biologically meaningful parameters are useful for the characterization and interpretation of observed differences between crops and environmentally induced changes within a species. Werker and Jaggard (1997) extended some classical approaches of asymptotic growth models including a decay parameter for senescence or stress induced decrease after a maximum as observed for leaf area or soil cover. Root distribution has been found to frequently follow an exponential or linear decrease with depth (Gerwitz and Page, 1974; Prasad, 1988). Silva and Rego (2003) used a two parametric exponential model to study differences in the depth distribution of the cumulative rooting density for different Mediterranean shrubs.

Image analysis has substantially facilitated and improved data acquisition for describing both aboveground and of root system characteristics of plants. Richardson et al. (2001) and Karcher and Richardson (2005) used image analysis for characterizing the ground cover dynamics of turfgrass. Bouma et al. (2000), Richner et al. (2000) and Himmelbauer et al. (2004) presented detailed studies on the capability and constraints of image analysis systems for root parameter measurement.

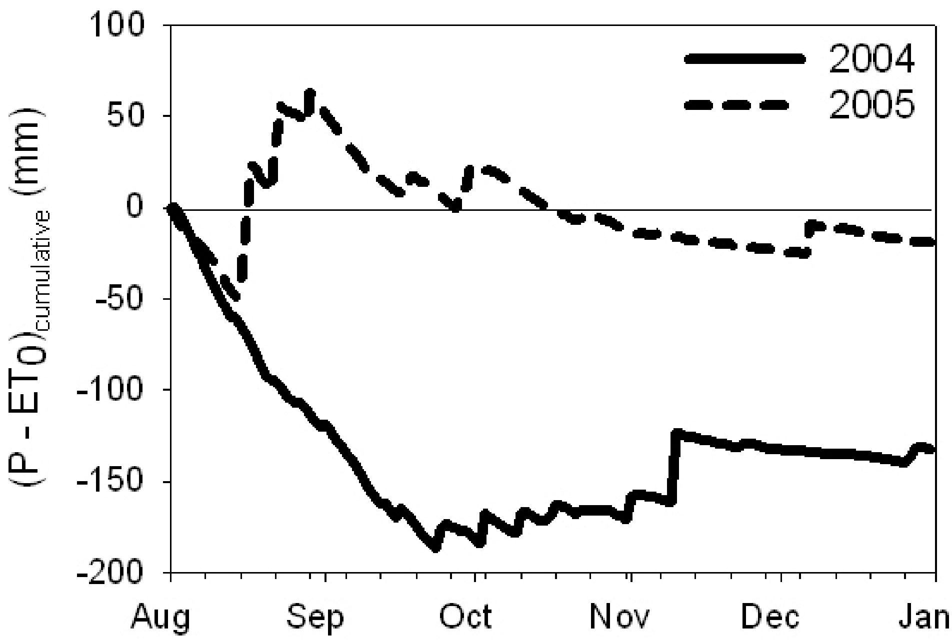
The objective of our present work is (i) to characterize four commonly used cover crop species of different plant families and with different root systems in relation to groundcover development and several root parameters in the main rooting zone and (ii) to asses the stability of growth dynamics and rooting pattern in relation to the inter-annual variability in climatic conditions, particularly rainfall distribution by (a) using mixed model analysis of variance and (b) applying existing growth and root distribution functions to the observed cover crop data.

5.2 Methods

5.2.1 Climatic growth factors

The two experimental years showed substantial differences in the climatic growth factors during the cover crop vegetation period. In 2004 cumulative temperatures resulted in a temperature sum about 100°Cd higher than in 2005. Cumulative photosynthetic active radiation was about 160 MJ m^{-2} higher in 2004. Particularly rainfall distribution varied substantially between both years. In 2004 dry conditions occurred at the time of seeding and germination of the cover crops, while later in the vegetation period from mid September to mid November there was frequent rainfall. In 2005 on the contrary, August was characterized by very high precipitation accounting for 67 % of the total rainfall during the cover crop vegetation period before winter. After the 29 September until 5 December, only 11 mm of rain fell resulting in severely dry conditions during the main cover crop growing period. Fig. 5.1 shows the climatic water balance deficit for the two years. Although the cumulative deficit is substantially less in 2005, it can be seen that between October and December a continuous negative balance between precipitation and reference evapotranspiration occurred. In 2004 the overall higher climatic water balance deficit results from the dry conditions until mid September when the evaporative demand of the atmosphere was still high, while it shows a decreasing tendency for the later measurement period when rainfall exceeded the cumulative evaporative losses.

Figure 5.1 Climatic water balance.



5.2.2 Above ground biomass and soil cover measurements

Ground cover of the cover crops was measured four times during the growing period by image analysis of digital pictures. Three digital photos were taken per plot from a constant height of one meter above the ground. Colour images, saved as JPG format, had a common size of 640 x 480 pixels. Image analysis of percent ground cover was performed using the software SigmaScan Pro5 (SPSS Inc, 1999). A green colour threshold was defined within a hue ranging from 55 to 113 and a saturation value between 11 and 100. All pixels in the image that represent the pre-selected colours are overlaid by a uniform yellow overlay colour. Ground cover is calculated as the number of pixels of the overlay colour by the total number of pixels of the digital image. The analysis was done using a macro presented by Karcher and Richardson (2005) for batch analysis of digital images.

Aboveground biomass was determined from a sample of 1 m^2 per plot taken at the end of the cover crop vegetation period at mid December when also root sampling was performed. The samples were oven dried at 105°C and dry weight was measured when samples had a constant weight.

5.2.3 Root sampling and analysis

Root samples were taken at mid December at the end of the cover crop vegetation period when the plants are likely to have reached their maximum growth before winter. Samples were taken using the soil core method (Böhm, 1979) to a depth of 40 cm covering the main root zone of the cover crops. Two samples were taken per plot, one on the plant row and one between two rows (row spacing: 15 cm) in order to assess the spatial distribution of the roots. The soil core with a total volume of 1583 cm^3 was divided in three sub-samples from 0-10 cm, 10–20 cm and 20-40 cm soil depth. In the laboratory, roots were separated from soil by a hydro-pneumatic elutriator as described by Smucker et al. (1982). Roots were collected in a sieve with 0.5 mm mesh diameter. An extra sieve of 0.2 mm was placed at the outflow of the elutriator system to make sure that no fine root material was lost. Debris and dead roots were removed visually from the samples considering colour and flexibility of living roots. After cleaning, the root samples were stored in an alcohol solution (30 % isopropanol) in a refrigerator at 4°C until further analysis. For image analysis, the roots were washed from the alcohol solution and coloured with a warmed Azur-Eosin-Methylenblue Giemza solution. Scanning of the coloured roots was done with an Epson Expression/STD 1600 scanner equipped with two light sources both from below and above. Scanning resolution was 300 dpi. Root images were stored in a TIFF format and evaluated for root length, surface area and root diameter using the WinRhizo 4.1 image analysis software. The image analysis has been described in detail by Himmelbauer et al. (2004). After image analysis, root weight was determined by drying the samples for 48 hours at 60°C until constant weight.

5.2.4 Soil cover parameters

In order to characterize the growing pattern of the cover crops concerning soil coverage, a growth and decay model presented by Werker and Jaggard (1997) for the evaluation of foliage cover of sugar beet crops based on the classical logistic Gompertz equation was fit to the measurement data.

$$y_i = y_{\max} \exp\left(\mu_{\min}(t_i - t_{\max}) - \frac{\mu_{\min}}{k}(1 - e^{-k(t_i - t_{\max})}) \right) \qquad (5.1)$$

where y_i (%) is ground cover at day t_i (d) after sowing, y_{max} (%) is maximum ground cover, μ_{min} (% d^{-1}) is the decay rate, t_{max} (d) is the number of days until maximum ground cover is reached and k (-) is a rate constant that determines how fast the initial growth rate approaches μ_{min}.

5.2.5 Root distribution function

A root distribution function presented by Silva and Rego (2003) was fitted to the cumulative root fraction for root length density and root surface area density.

$$Y_r = \frac{1}{1 + \left(\frac{Maxd - D}{d \cdot D} \right)^c} \qquad (5.2)$$

where Y_r (-) is the cumulative root fraction, D is soil depth (cm), Maxd (cm) is the maximum depth of the studied profile (i.e. 40 cm) and *c* and *d* are model parameters. The cumulative root fraction was obtained by dividing the root density at each depth by the sum of root densities of the soil profile and then computing the cumulative series of theses values for all depths. To study differences in the root distribution, the D_{50} parameter, showing the depth corresponding to 50 % of the cumulative root fraction, was calculated by:

$$D_{50} = \frac{Maxd}{(d + 1)} \qquad (5.3)$$

High values of D_{50} are associated to deep rooting whereas low values are associated to a higher concentration of roots close to the soil surface.

5.2.6 Statistical evaluation

The growth and root distribution models (Eq. 5.1 and 5.2) were fitted to the measurement data by non-linear regression based on a Levenberg-Marquardt algorithm using the procedure NLIN of the SAS software package (SAS Institute Inc, 2004).

An analysis of variance was performed to determine if there were significant differences between years, cover crop treatments, measurement date (for soil cover), soil depth and sampling position (for root parameters). All data were first checked for normality using a Kolmogorov-Smirnov test. Most root parameter, except root diameter, showed a positive skewness. Therefore a logarithmic transformation was applied to achieve normality.

When applying an analysis of variance including repeated measurements, i.e. in our case the measurement dates for the soil cover analysis and soil depths as well as sampling position for the root parameters, the assumption of independence between the levels of the factors under consideration is not fulfilled. To perform the analysis of variance, the correlation structure of the repeated measurement factors must be defined. Following the outlines of Piepho et al. (2003, 2004), we used the procedure MIXED of the SAS software package to find an appropriate correlation model by the Akaike Information Criterion (AIC). For soil cover analysis with sampling date as the repeated measure, a first order autoregressive correlation structure was used. For root parameters with two repeated factors a crossed unstructured x compound symmetry model [un x cs] showed the best fit to our data.

In case of significant effects in the Wald-F-statistic with $p < 0.05$, comparison of means was done using a two sided t test.

5.3 Results

5.3.1 Soil cover

For the statistical comparison of percentage ground cover between both years, measurements of the second year were adjusted to the same sampling date of the first year, i.e. the same number of days after sowing. Analysis of variance resulted in a significant interaction effect between year x sampling date x cover crop ($p = 0.040$). Table 5.1 shows the comparison of means between the cover crops for each year as well as for the same cover crop species between the two years at each measurement date.

Table 5.1 Development of ground cover of different cover crops.

	Phacelia		Vetch		Rye		Mustard		Mean	
	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
	Percent Ground Cover (%)									
17 Sep	21.4*abA**	31.8*acA*	10.1*bA*	56.1*bB*	30.0*aA*	29.3*cA*	32.3*aA*	46.9*abA*	23.4*A*	41.0*B*
15 Oct	58.1*aA*	43.5*aA*	31.5*bA*	89.7*bB*	48.1*aA*	49.8*aA*	60.3*aA*	69.9*bA*	49.5*A*	63.2*B*
11 Nov	77.1*aA*	33.9*aB*	59.8*bA*	84.3*bB*	56.7*bA*	24.8*aB*	69.0*abA*	58.6*cA*	65.6*A*	50.4*B*
10 Dec	78.3*aA*	28.5*aB*	61.7*bA*	81.8*bB*	53.4*bA*	18.1*aB*	57.3*bA*	56.3*cA*	62.7*A*	46.2*B*

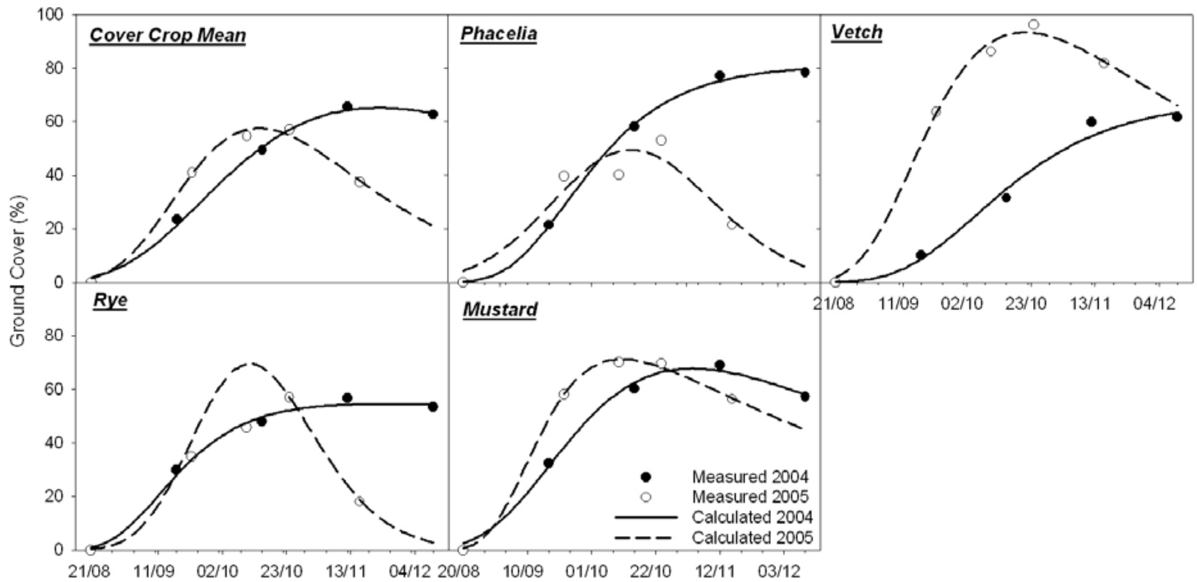
**Upper-case letters refer to the comparison of the same species at one measurement date between the two years, lower-case letters refer to the comparison between species for one measurement date for the same year.*

Comparing the two experimental years, the average percentage of ground cover showed significant differences throughout the entire growing season of the cover crops. For the first sampling dates, cover crops achieved a significantly higher ground cover in 2005. On the contrary, soil cover in 2004 was 30 % higher in November and 36 % higher in December compared to the year 2005. When analysing the yearly differences of the single cover crop species, mainly vetch had a significantly lower ground cover during the first year for the sampling dates in September and October. The other cover crops did not show significant differences during the early growth period. For the measurement dates during late autumn, we found significantly less soil coverage in the second year for all cover crop species with the exception of mustard that showed a similar ground cover development in both years.

Comparing the cover crop variants within one year, in 2004 phacelia reached the highest maximum ground cover. Vetch showed a substantial delay in ground cover development until mid October in this year. However, the vetch plants partially recovered this delay increasing ground cover until the last measurement date, while both rye and mustard showed a decrease between mid November and mid December. In 2005 the maximum ground cover of all the cover crop species was measured at mid October. At this stage, vetch and mustard had significantly higher values than phacelia and rye. Vetch already differed significantly from rye and phacelia at the first measurement date. A general decrease in ground cover towards late autumn was found. For the late season sampling dates, vetch could maintain the highest ground cover. Also mustard had a significantly higher late season ground cover than phacelia and rye. Phacelia and rye showed the highest decrease towards the end of the vegetation period with a final value of 66 % of its measured maximum for phacelia and only 36 % for rye.

Parameters characterizing the soil cover dynamics of the cover crops were determined by fitting Eq. 5.1 to the measurement data starting with zero ground cover at the day of sowing. For this analysis differences in the sampling dates between the two years were not adjusted as for statistical analysis. Fig. 5.2 shows the data points of the single sampling dates and the calculated growth and decay curves.

Figure 5.2 Soil cover measured and calculated using a growth and decay model ***(Eq. 5.1)*****.**



In 2004 there was no decay measured over the sampling period for phacelia and vetch. Consequently the decay parameter μ_{min} is zero and Eq. 5.1 reduces to the classical Gompertz growth function. The data generally were described well by the applied model. However, as there were only five points no significant fitting of the model could be achieved for phacelia and rye in 2005. Table 5.2 shows the parameters describing growth and decay and the significance level for the model fit. The average growth dynamics resulted in a lower maximum soil cover for the year 2005. The time to reach the maximum mean ground cover was 39 days earlier in 2005 compared to 2004 which is also expressed by a higher value of the rate constant k describing the speed at which the initial growth rate approaches μ_{min}. The high negative value of the final decay rate shows the substantially higher average soil cover decrease under the dry conditions in the second year. The highest maximum soil cover was predicted for vetch in 2005 at 62 days after sowing. The highest value for the growth rate k was found for mustard in 2005. Both rye and phacelia had a very high decay rate in 2005. However for both crops the model did not show a satisfactory fit and thus the model parameters can not be considered reliable descriptors of the growth and decay dynamics of these crops.

Table 5. 2 Growth and decay function parameters characterizing ground cover of cover crops.

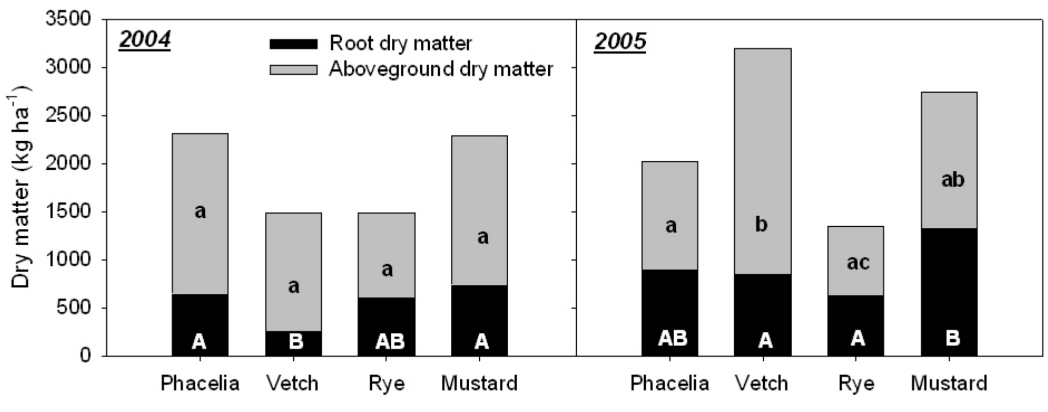
			Phacelia		Vetch		Rye		Mustard	
	Ø 2004	Ø 2005	2004[a]	2005	2004[a]	2005	2004	2005	2004	2005
y_{max} (%)	65.2	57.6	81.0	49.4	68.7	93.3	54.6	69.5	67.8	71.3
t_{max} (d)[b]	94	55	34	55	47	62	98	52	75	52
k (d^{-1})	0.031	0.036	0.052	0.005	0.041	0.049	0.062	0.021	0.039	0.069
μ_{min} (d^{-1})	-0.007	-0.031	0	-0.268	0	-0.011	-0.001	-0.123	-0.009	-0.010
p	*0.047*	*0.052*	*0.001*	*ns*	*0.007*	*0.046*	*0.054*	*ns*	*0.054*	*0.023*

[a]*Gompertz logistic growth function (no decrease measured).*
[b]*t_{max} in the asymptotic Gompertz equation represents time to maximum growth rate, while for the growth and decay function it represents time to achieve the maximum ground cover value y_{max}.*

5.3.2 Aboveground and root biomass

Aboveground and root biomass are shown in Fig. 5.3. There was no significant difference in mean aboveground biomass between the two years, while root biomass showed a significant main effect of the year ($p<0.001$) with the average cover crop root dry matter being 65 % higher in 2005 compared to 2004.

Figure 5.3 Aboveground and root dry matter. *(Bars with the same letter are not significantly different at p < 0.05. Lower case letters refer to aboveground dry matter, upper case letters refer to root dry matter.)*



Analysis of variance indicated a significant year x cover crop effect for both aboveground (p=0.01) and root biomass (p=0.05). For aboveground dry matter, differences between the cover crops in 2004 were below statistical significance, while in 2005 a significantly higher aboveground dry matter was found for vetch compared to phacelia and rye. For root biomass vetch had the lowest value in 2004 being significantly less than phacelia and mustard. In 2005 mustard differed significantly from both vetch and rye.

Table 5.3 shows the ratio of root to shoot weight for the different cover crops. Statistically only the year main effect was significant (p=0.047) with a higher root to shoot ratio in 2005. A general tendency of all cover crops towards a higher root to shoot ratio for the dry conditions in autumn 2005 can be seen except for vetch where the very low aboveground biomass in 2004 resulted in a rather high proportion of the roots to the total dry matter growth.

Table 5.3 Root to shoot ratio of cover crops.

	Root : Shoot Ratio (-)	
	2004	2005
Phacelia	0.40	0.77
Vetch	0.40	0.37
Rye	0.69	0.89
Mustard	0.54	0.95
Ø[a]	0.51*a*	0.75*b*

[a]*Different letters indicate significant difference at p < 0.05.*

5.3.3 Root parameters

Analysis of variance of root length density and root surface area density revealed a significant interaction of year x cover crop (p=0.001 and 0.002 respectively) and year x soil depth (p<0.0001 for both parameters). Differences in the measured average root diameter were only significant for the cover crop (p=0.02) and soil depth (p=0.02) main effects without an interaction effect with the year. Table 5.4 shows the mean root length density and surface area density for the cover crops in 2004 and 2005 as well as the root diameter as a mean across both years. For both, root length density and surface area density, only rye did not differ significantly between both years, while all other species had substantially higher values in 2005.

Table 5.4 Root length density, root surface area density and root diameter of cover crops.

	Root Length Density $cm\ cm^{-3}$		Root Surface Area Density $cm^2\ cm^{-3}$		Root Diameter mm
	2004	2005	2004	2005	Ø 2004-2005
Phacelia	2.2*aA***	6.3*aB*	0.19*aA*	0.41*aB*	0.34*a*
Vetch	0.7*bA*	3.2*bB*	0.08*bA*	0.32*abB*	0.47*b*
Rye	2.8*aA*	3.8*bA*	0.26*aA*	0.28*abA*	0.34*a*
Mustard	1.3*cA*	3.6*bB*	0.09*bA*	0.25*bB*	0.28*a*

**Upper-case letters refer to the comparison of the same species between the two years; lower-case letters refer to the comparison between species for the same year.*

Using the coefficient of variation to describe annual variability, rye showed the lowest variability in root length density and root surface area density with a coefficient of variation of 44.4 % and 40.3 % respectively. The highest variability in the rooting pattern was found for vetch with coefficients of variation of 66.6 % and 60.5 % respectively. The high variability of vetch rooting parameters is probably also related to the particularly high yearly differences in aboveground biomass accumulation resulting in a substantially lower overall availability of assimilates for root biomass growth in 2004.

Comparing the individual crops within one year, vetch had a significantly lower root length density in 2004 compared to all other cover crops. The highest values were found for rye and phacelia. Mustard had an intermediate root length density. In 2005 there were only small differences between vetch, rye and mustard, while phacelia showed significantly higher values than all other species. Root surface area density was lowest for vetch and mustard in 2004 being statistically different from both, phacelia and rye. In 2005, only mustard with the lowest surface area density differed significantly from phacelia. Differences in root diameter were found between vetch and all other cover crops with roots having a significantly higher average diameter for this legume species.

Root length density of phacelia was particularly high in the upper soil layer (0-10 cm soil depth) being 33 % and 56 % above the cover crop mean in 2004 and 2005, respectively. Root surface area density was highest for phacelia too, however differences to the other crops were less pronounced.

For mustard root length density ranged from a mean of 1.3 cm cm^{-3} in 2004 to 3.6 cm cm^{-3} in 2005 with a maximum of 6 cm cm^{-3} in the upper soil layer being in the range found for other brassica species by Vos et al. (1998). For root surface area density mustard showed very low values reflecting the low average diameter of mustard roots that resulted in a surface area even less than for vetch in 2005 in spite of a slightly higher root length density.

Concerning the depth distribution, root length density and root surface area density were significantly different between all depths in 2004, while in 2005 differences between the average value at -5 and -15 cm were not significant for root length density. Also for root surface area density the decrease between the first two measurement depths, although being significant in both years, was smaller in the second year. The average root diameter was higher near the soil surface compared to the deeper soil layers with a significant difference found between -5 and -15 cm soil depth.

The depth profile of both root length density and root surface area density showed an exponentially decreasing trend in 2004 and a more linear decrease in 2005 (Fig. 5.4).

Figure 5.4 Depth distribution of root length density, root surface area density and root diameter. *(Average over all cover crops. Bars with the same letter are not significantly different at p < 0.05. Lower case letters refer to comparison between two years at one soil depth, upper case letters refer to different soil depths for the same year.)*

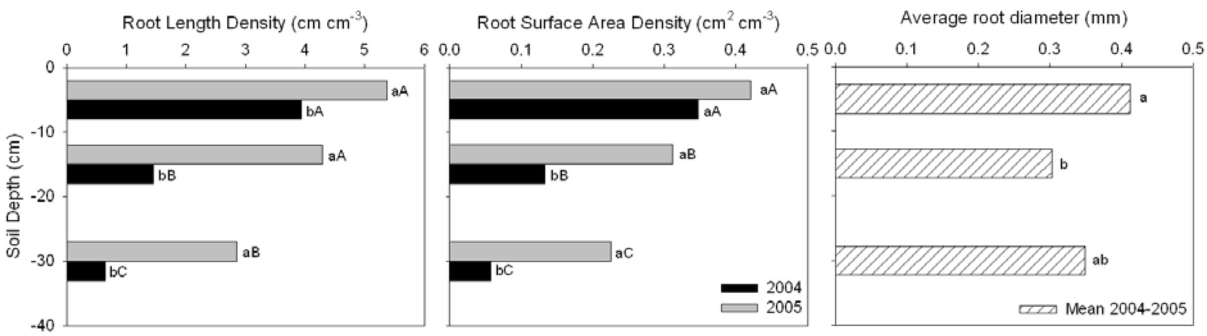
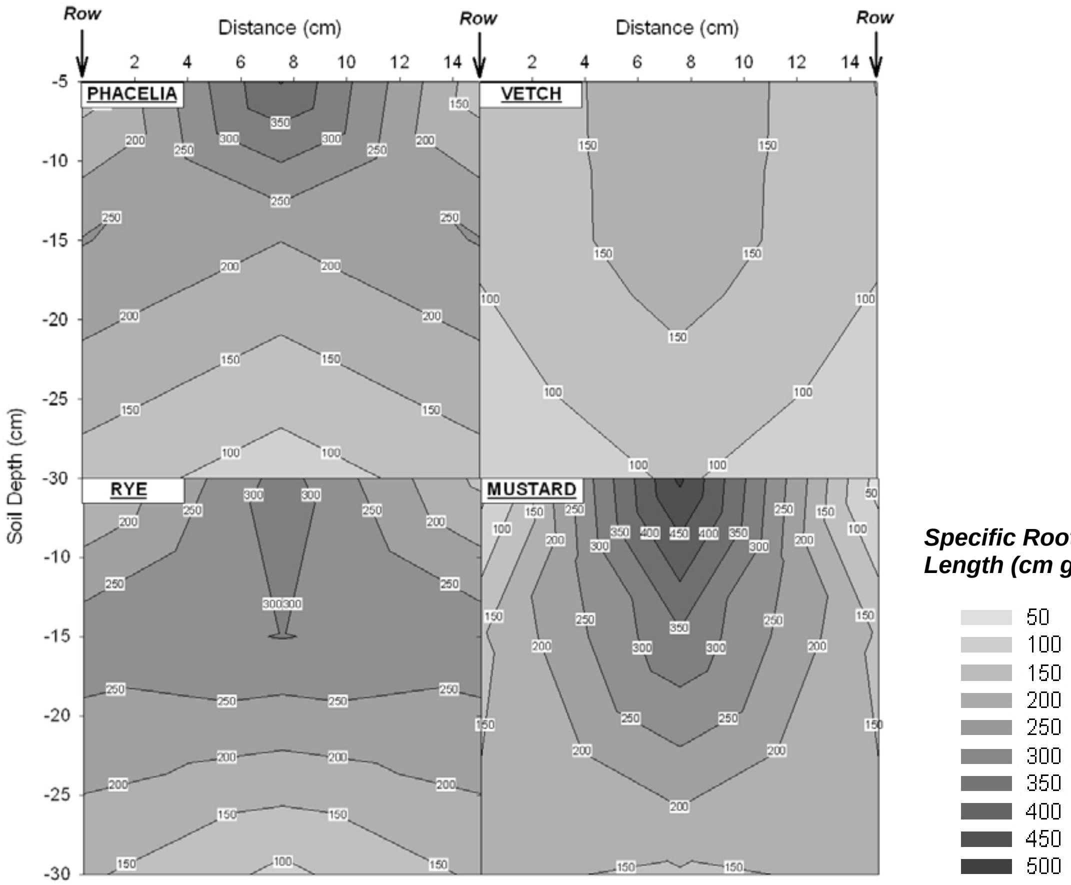


Figure 5.5 Spatial distribution of specific root length *(Average of two years).*



Analysis of variance of specific root length and specific root surface revealed a significant interaction effect between cover crop x soil depth x horizontal spatial distance (p=0.03 and p=0.01 respectively). As there was neither a significant interaction nor main effect of the year, these root properties give a good characterization of the different spatial rooting pattern of the cover crops both in the horizontal and vertical direction which is shown for the specific root length in Fig. 5.5. As specific root surface gives a similar spatial distribution, data for the specific root surface area distribution are not shown here.

Concerning the spatial distribution in the horizontal direction, all cover crops except vetch showed a significantly higher specific root length between the rows than in the row at -5 cm soil depth. The differences are particularly high for phacelia and mustard, both having a tap root typically accounting for much of the root weight but only a small root length. Mustard shows the same pattern of significantly higher specific root length between the rows than in the row also at -15 cm soil depth. At -30 cm there were no more significant differences of the values found below the plants and between two plant rows.

The vertical distribution in the row showed a maximum for phacelia and rye at -15 cm soil depth decreasing both towards the topsoil and towards higher soil depth. For mustard, specific root length in the row tended to increase particularly between the uppermost layer and -15 cm soil depth. Below -15 cm the increase was not significant. Vetch in general has a very homogeneous distribution of specific root length both in the horizontal and vertical direction, with the only significant difference being a decrease in the row between -15 and -30 cm soil depth. Between the rows a general decrease in specific root length with depth has been found, being significant for all species except vetch between -15 and -30 cm soil depth.

Comparing the different cover crops, it can be seen that mustard had a significantly lower specific root length at -5 cm depth in the row than all other species. At -15 cm, where phacelia and rye had their maximum specific root length in the vertical direction below the plants, both species had significantly higher values than vetch and mustard. At -30 cm only vetch differed significantly from all other cover crops having the lowest specific root length. Between the rows, vetch had a significantly lower specific root length in -5 cm compared to phacelia and mustard, while below -5 cm there were no significant differences between the variants.

Finally we fitted a distribution function (Eq. 5.2) to the cumulative root length density and surface area density data to calculate the D_{50} parameter (Eq. 5.3) expressing the depth where 50 % of the cumulative root density are reached. The two parameter function fitted well to both root length density (Fig. 5.6) and root surface area density (figure not shown). Table 5.5 shows the values of the D_{50} parameter as well as the significance level of the curve fit for both root length density and root surface area density. For all cover crops the model showed high significance in describing the measurement data.

Figure 5.6 Cumulative distribution of relative root density with depth measured and calculated ***(Eq. 5.2)*****.**

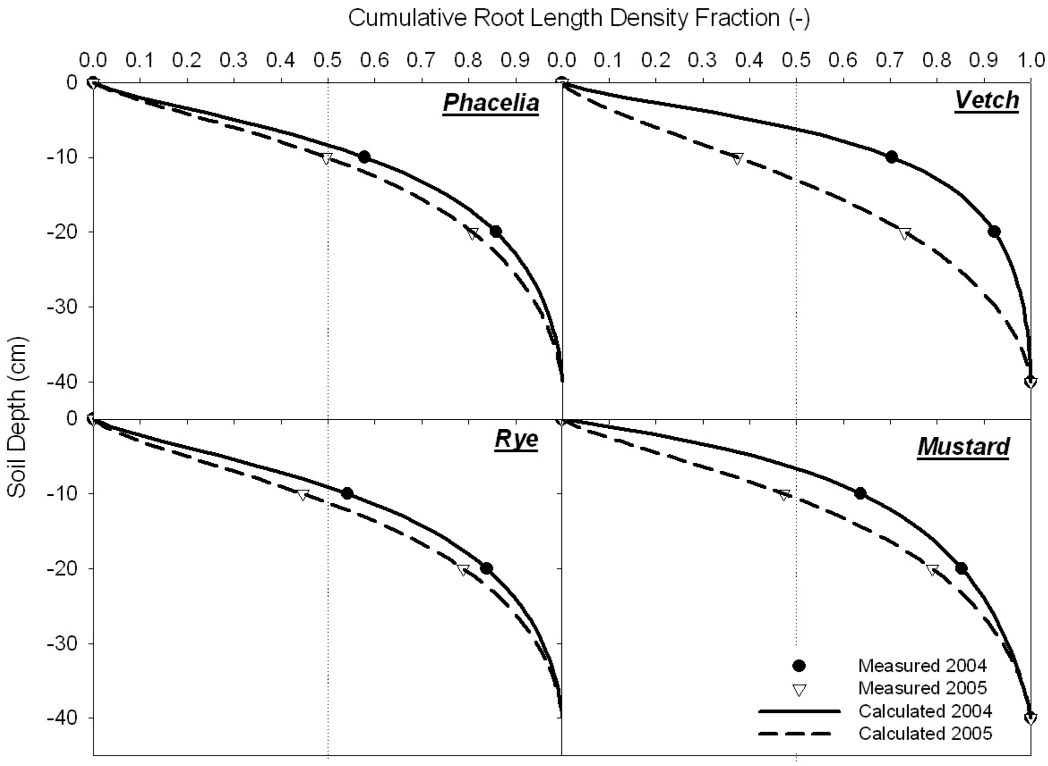


Table 5.5 Depth distribution parameter for root lenght density (RLD D_{50}) and root surface area density (SAD D_{50}) of cover crops *(cf. Eq. 5.3)***.**

	RLD D_{50} (cm)		SAD D_{50} (cm)	
	2004	2005	2004	2005
Phacelia	-8.4	-10.1	-8.6	-11.0
Vetch	-6.2	-13.1	-6.5	-12.6
Rye	-9.1	-11.2	-6.9	-10.4
Mustard	-6.6	-10.7	-7.2	-11.2

The depth of 50 % cumulative root density was between -6.2 cm and -13.1 cm for length and between -6.5 cm and -12.6 cm for surface area. In average, the depth of D_{50} was 54 % higher for length and 57 % higher for surface area in 2005. Both phacelia and rye had substantially lower annual differences in the depth of D_{50} for root length density compared to vetch and mustard. Phacelia also showed the lowest annual variability for root surface area density. Vetch on the contrary had the most pronounced annual differences in root penetration with nearly twice the depth where 50 % of root density was found in 2005 compared to the value calculated for the first year.

5.4 Discussion

A detailed characterization of both ground cover and root parameters of cover crops is essential to understand their impact on several soil physical and hydrological processes. Differences in the amount of soil cover can modify the energy balance at the soil surface and thereby influence the amount of evaporative water losses to the atmosphere (Wagner-Riddle et al., 1997; Bodner et al., submitted). Plant roots not only determine the water and nutrient uptake of the crops, but also influence soil structure formation and stabilization in the main rooting zone. Four cover crop species frequently used in the frame of European agro-environmental programmes were investigated for two years in a field trial in the semi-arid region of Eastern Austria. Emphasis was given to their growth performance in relation to inter-annual differences in climatic condition.

5.4.1 Climatic conditions and aboveground growth parameters

The two experimental years differed substantially in the meteorological growth factors, particularly in rain distribution and the potential occurrence of water stress as reflected by the climatic water balance deficit. In 2005 the accumulated temperature sum with a baseline temperature taken at 5°C was 11 % less than in 2004 and the cumulative photosynthetic active radiation (PAR) was 16 % below the value of 2004. Plant species used for cover cropping in central European agriculture are generally adapted to lower temperatures and the different temperature sums between the two experimental years are probably of minor importance for explaining different behaviour in biomass accumulation and soil cover development. The difference of total aboveground biomass in 2005 compared with 2004 was -32 % for phacelia, -19 % for rye and -8 % for mustard. Vetch was an exception as its aboveground biomass growth was substantially higher in 2005 by as much as +90 %. Taken a lower value of PAR by -16 % in 2005, the differences in biomass growth for both phacelia and rye would be higher than expected for potential growth limited by the available radiation for photosynthesis only, while dry matter accumulation of mustard showed less difference than expected from the lower accumulated PAR and vetch even had a higher biomass in 2005. Thus the amount and distribution of precipitation determining soil moisture availability at different growing stages can be assumed to be the essential factor for cover crop performance.

In 2005 high rainfall occurred during August. The resulting high soil water availability allowed a fast germination and early development of the crops. The maximum soil cover was achieved earlier in 2005 and was lower compared to the year 2004. In 2005 all cover crops showed a soil cover decrease for the two late measurement dates at mid November and mid December. The persistent climatic water balance deficit during the main growing period of the cover crops in 2005 suggests that these results are due to the occurrence of drought stress resulting in premature wilting of leafs and an accelerated senescence. In 2004 only mustard showed a reduction in soil cover towards the end of the vegetation period that is most likely explained by low temperatures and the onset of freezing over night.

Mustard was found to be less susceptible to differences in growing conditions. Although soil cover development of mustard was initially delayed due to the dry seeding conditions in 2004 compared to a faster growth rate in 2005, the accumulated aboveground biomass differed by only 8 % and the final percentage of soil cover by less than 2 % between both years. The coefficient of variation can be used to quantify both, the homogeneity of the cover crop establishment in the field and its stability over the two years. The coefficient of variation for mustard was 18.6 % for aboveground dry matter and 23.9 % for final soil cover.

The growth dynamics of vetch showed the highest sensitivity to the soil moisture shortage for germination in August 2004. Vetch with the highest seed weight of the cover crops investigated has the highest water demand to initiate germination. The adverse germination conditions in 2004 are reflected by the delayed ground cover at the early growth stage in mid September when only 43 % of the cover crop mean value was achieved. Soil cover was most variable at the initial growing stage with a coefficient of variation of 77.5 % that decreased continuously for the later measurement dates towards 30.1 %. The reduction in soil cover before winter was very small for the winter hard vetch plants; in 2004 even no decay phase was observed until mid December. For the aboveground biomass the coefficient of variation for vetch was 65.6 % being substantially higher compared to all other variants.

Phacelia was most sensitive to water shortage during the main growing period between September and October. While in 2004 phacelia had the highest total ground cover, in 2005 its maximum cover did not exceed 50 % and a final value of only 28.5 % was achieved. As wilting and senescence of phacelia leaves induced a change in colour toward anthocyanic red in late autumn, image analysis however might have lead to a slight under-estimation of the final soil cover. The green colour threshold only reflects leaves that still maintain their photosynthetic functionality, while senescent and fallen leaves are probably not fully captured by the method although they protect the soil surface as plant and mulch cover. The coefficient of variation for the phacelia aboveground dry matter was 25.5 %, soil cover had the highest variability for the final sampling date with a coefficient of variation of 53.8 %.

Rye had the lowest total biomass growth and only achieved a low soil cover being around 50 % of the surface covered by the plants. Particularly in 2005 there was a very high reduction in the percentage of soil cover for rye towards the end of the vegetation period. This observation however may also be related to the occurrence of barley plants within the rye cover crop from volunteer seeds of the preceding cash crop. While a colour discrimination of rye and barley was not possible during the early stages, in the later vegetation period spring barley was visibly affected by the lower temperatures and pests resulting in yellow discolouration of the leaves allowing for differentiation in the image analysis. Thus the high final reduction in rye ground cover could be related to an initial over-estimation due to the contribution of barley plants to the overall soil cover.

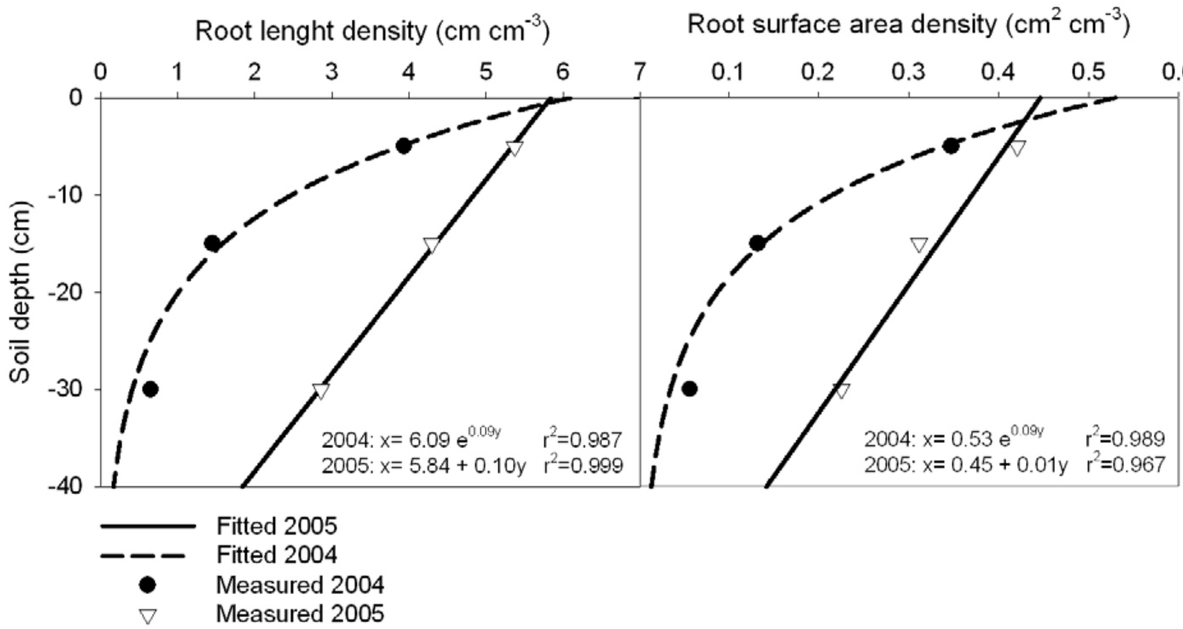
In spite of the limited aboveground growth of rye, our results revealed that this cover crop species has a particularly high potential of belowground biomass accumulation with an average root to shoot ratio of 0.79 being above the mean value of the investigated cover crops. Only mustard in 2005 had a higher root to shoot ratio, which is related to its strong taproot that accounts for a high amount of the total root weight.

5.4.2 Cover crop root characteristics and reaction to dry conditions

Only few studies provide detailed measurements of cover crop root parameters. Wyland et al. (1996) measured the root lenght density of rye and phacelia used as cover crops. For phacelia they found an average root length density to a depth of 45 cm of 2.8 cm cm^{-3} and for rye of 4.7 cm cm^{-3}. Sainju et al. (1998) used minirhizotrons to determine cover crop root parameters and found significantly higher root length density in 0-30 cm soil depth for rye than for vetch and clover with very high values for the rye crop of about 20 cm cm^{-3}. Vos et al. (1998) gave values between 4 and 6 cm cm^{-3} for winter rye and forage rape used as cover crops. In our study average root length densities down to -40 cm soil depth ranged from a lowest value of 0.7 cm cm^{-3} for vetch to a highest value of 6.3 cm cm^{-3} for phacelia. In the upper soil layer (0 to -10 cm) the lowest value measured was 2.4 cm cm^{-3} for vetch and 9.4 cm cm^{-3} for phacelia was the highest, being within the range of root densities found by other authors for different cover crop species.

Analysing the sensitivity of the cover crop rooting patterns to the different climatic growing conditions of the two experimental years, the dry conditions in 2005 generally induced a more intense root growth while reducing aboveground biomass. The mean root to shoot ratio of the cover crops was significantly higher in 2005 compared to 2004. Water shortage during the main growing period in 2005 resulted in both, higher absolute values of the measured root density parameters as well as a tendency of the cumulative relative root densities to shift to higher soil depth (cf. Fig. 5.6). In 2004, the mean values of root length density and root surface area density could be approximated by an exponential decrease with depth, while in 2005 they fit well to a linear decrease (Fig. 5.7).

Figure 5.7 Influence of inter-annual climatic variability on root distribution. Exponential and linear distribution of average root length density and root surface area density with depth.



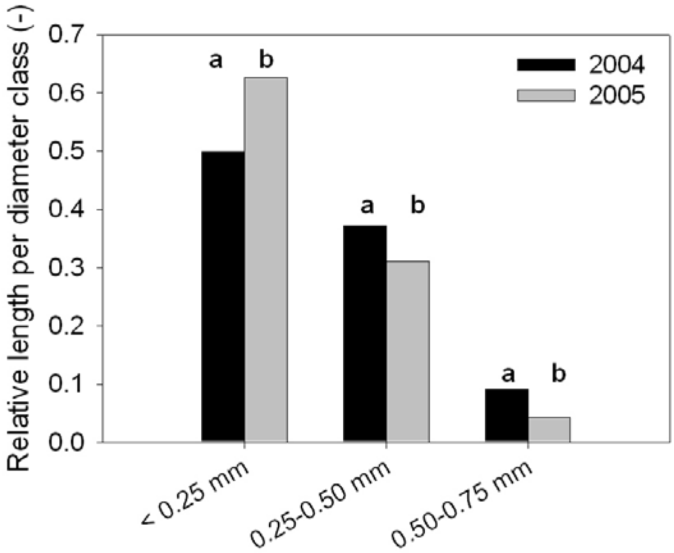
Both, exponential and linear functions have been used to describe root distribution with depth for water uptake modelling. The exponential function fitted to the 2004 data corresponds to the Gerwitz and Page equation (Gerwitz and Page, 1974), while the linear model corresponds to the approach used by Prasad (1988).

Studying the influence of root parameters on water uptake, De Willigen et al. (2000) give a threshold value for root length density between 0.5 and 1.0 cm cm^{-3} being sufficient for plants to exhaust the readily available water from a given soil layer. Generally root length density of the cover crops was above this value with the exception of vetch below 20 cm soil depth in 2004. However, as in 2004 there was sufficient rain during the main growing period refilling the upper soil layer and also vetch had a root length density of 2.4 cm cm^{-3} near the soil surface, generally root length density should not have been limiting for water uptake.

When water availability was limited due to a lack of rainfall in 2005, the highest reduction in aboveground biomass was found for phacelia with -32 % together with a substantial decrease in soil cover. Phacelia showed the lowest change in the depth where 50 % of the cumulative root density was found between the two years. This indicates that the capacity to shift rooting density in depth rather than a high absolute value of root density in the upper soil layer is decisive to maintain the plant water demand when the upper soil layers are depleted. This is confirmed by vetch showing the strongest ability of shifting root concentration to deeper soil layers under the dry growing conditions of 2005. In this way a high aboveground biomass could be accumulated and only a low reduction in soil cover occurred towards the late season in spite of a low amount of precipitation.

Additionally, water shortage might change the carbon allocation strategy of plants towards the formation of more fine roots (Huang and Fy, 1998). In total, between 96 % and 98 % of the total root length of the cover crops was within a root diameter class < 0.75 mm. The dry autumn 2005 promoted the formation of finer roots with a diameter < 0.25 mm accounting for 63 % of the total root length in 2005, while in 2004 only 50 % of the roots were found in this diameter class (Fig. 5.8).

Figure 5.8 Average root length of the cover crops per root diameter class. *(Bars with the same letter are not significantly different at $p < 0.05$.)*



An important parameter revealing the carbon allocation strategy of a plant species within the root system is specific root length (Atkinson, 2000). The spatial pattern differed particularly between species with a high amount of root biomass concentrated in a primary tap root accounting for less root length and those having a more homogeneous distribution of root length per unit weight (cf. Fig. 5.5). Concerning soil physical effects, tap rooting cover crops have been shown to alleviate soil compaction (Williams and Weil, 2004), while an even biomass allocation in an intense system of fine roots favours aggregate stabilization (Jastrow et al., 1998). The tap root system is particularly pronounced for mustard which penetrates the soil below the plant with a strong primary root that accounts for a high amount of root biomass but only little root length. Specific root length of the lateral branches suggests an intense system of thin roots penetrating the soil horizontally. The high values of specific root length between the rows are probably a result of overlapping roots of neighbouring plants.

For phacelia specific root length suggests a less developed primary root compared to mustard. The horizontal gradient between the specific root length below the plant, reflecting biomass allocation in the primary root, and the lower order lateral roots was less than with mustard. Below -15 cm soil depth, in contrast to mustard and vetch, the specific root length of phacelia was lower between the rows than below the plants. This indicates less lateral root growth and only limited overlapping between adjacent rows.

Rye showed the typical pattern of grass species characterized by a fibrous root system with seminal roots originating from the seed and adventitious roots. While the higher specific length near the seed and stem base shows thicker roots with less length per unit weight, below -15 cm a very homogeneous rooting with roots of the same specific root length is found both below the plant and between the rows.

Also the vetch plants showed a small horizontal gradient in specific root length, revealing a homogeneous assimilate allocation to roots of different order as described by Kutschera (1960). Similar to the observations made for mustard, specific root length between the rows is higher in the main rooting zone. This reflects overlapping root systems of neighbouring plants and, in spite of the generally low root length density of the vetch cover crops, an intense lateral root expansion with a homogeneous penetration of the soil also in the horizontal direction.

5.5 Conclusions

During a two year field trial, four commonly used cover crop species were investigated regarding their growth traits with particular emphasis on soil cover and several root parameters in the main rooting zone. Cover crop growth was mainly influenced by rainfall distribution over the vegetation period. As pointed out by Arora and Boer (2003) root distribution is not constant over the growing period of a crop. Our results show that parameters used to characterize the root distribution of a plant species can substantially vary with changing environmental conditions. Particularly interactions with soil moisture will modify not only maximum rooting depth, but also the root distribution over the soil profile. A good approximation of cover crop root distribution was achieved by an exponential decrease function under conditions of sufficient rainfall and soil moisture in the upper soil layer, while water stress in the topsoil induces a lower decrease with depth tending towards a linear distribution function.

Concerning the use of cover crops in semi-arid environments our results suggest that mustard provides highest stability to variable climatic conditions with high soil coverage also under dry conditions, a high root biomass with a strong tap root and an intense formation of fine lateral roots. Vetch was most sensitive to soil moisture shortage for germination and early growth with highest inter-annual variability in aboveground biomass. In case of sufficient rainfall for germination and early development, vetch is able to develop an intense aboveground biomass and a nearly complete soil cover. Its rooting pattern is characterized by a high average root diameter and a rather low root density in the main rooting zone. However we found a homogeneous rooting in horizontal as well as in vertical directions and a sensitive reaction of root density distribution towards higher soil depth under dry conditions, thus providing sufficient water for a high aboveground biomass growth. Rye had the lowest aboveground biomass and a maximum soil cover below 60 % even under favourable growing conditions. A mayor advantage of the rye cover crop is its high root to shoot ratio and an intense and homogeneous rooting pattern in spite of its limited aboveground biomass growth. The root system of the rye cover crops showed little sensitivity to the inter-annual variation in growing conditions. Phacelia was susceptible to drought during the later growing stages with a substantial reduction of living soil cover. The rooting pattern of phacelia showed an intense root development concentrated near the soil surface with a substantial decrease in both the vertical and the horizontal direction compared to the other crops.

Image analysis provided a convenient way for both soil cover and root parameter measurement. Based on these data, characteristic parameters for the ground cover growth and vertical root distribution could be derived by applying basic growth and root distribution functions. Beyond statistical comparison of the single crops and their inter-annual variability, the model parameters allowed for a better interpretation of the crop specific behaviour under variable environmental conditions. Further investigations should be focused on exact relations between parameters of cover crop potential growth and their change in water limited environments. This can contribute to an improved model based scenario analysis of the potential of different cover crop species under a variety of climatic conditions for catching nitrate, stabilizing soil structure and controlling erosion.

5.6 Literature

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6 Cover crop evapotranspiration under semi-arid conditions using FAO Dual Crop Coefficient Method with water stress compensation

Abstract

Cover cropping is a common agro-environmental tool promoted by European and national authorities for soil and groundwater protection. If water is the limiting factor for the cash crop yield, knowledge about cover crops' water use is required for their sustainable integration in the crop rotation. Based on soil water measurements in a two years field experiment, the water balance for the growing period of four cover crop species (phacelia, hairy vetch, rye, mustard) compared to a fallow control was calculated. Water balance based calculations of actual evapotranspiration were compared to estimates using the FAO Dual Crop Coefficient Method. A water stress compensation function for dry conditions was integrated in the model to improve estimates of water uptake from deeper soil layers. We found good agreement between measured and modelled cumulative water losses to the atmosphere. Based on the modelling results, the structure of evapotranspiration was analysed concerning the proportion of soil evaporation and plant transpiration. Under dry conditions, cover crops showed higher total water losses compared to fallow during their main growing period as soil evaporation from fallow was reduced by water shortage in the upper soil layers while plants could deplete deeper layers. The amount of evapotranspiration did not differ from fallow when the upper soil layer was refilled by frequent rainfall in autumn. Water use efficiency was highest for phacelia (5.1 g mm^{-1}) and vetch (5.8 g mm^{-1}) and substantially lower for rye and mustard (2.8 g mm^{-1}). In general, cover crops reduced high evaporative losses from bare soil in late summer from the upper soil layer by fast and effective shading of the surface, conserving water for their transpiration demand. Additional plant water uptake from deeper layers during full cover crop development was limited due to the lower evaporative demand of the atmosphere in late autumn and reduced the potential of soil water storage depletion by the cover crops. The FAO method proved to be a useful tool to provide estimates on soil water depletion by cover crops and revealed soil cover, root distribution and rooting depth as important plant parameters of autumn and winter grown green manure crops on the evapotranspiration process.

6.1 Introduction

European agro-environmental programmes promote the use of cover crops in the crop rotation during autumn and winter following the harvest of cash crops to prevent leaching of soil nutrients, and to reduce runoff and soil erosion. Several studies have shown that permanent soil cover and high organic inputs of cover crops effectively contribute to a sustainable management of soil fertility stabilizing and improving soil physical properties (e.g. Roldán et al., 2003; Guangwei et al., 2006; Cherr et al., 2006).

In semi-arid and arid environments, cover crops can deplete the soil water availability for the following cash crops due to their transpiration demand thus causing possible yield reductions (Mitchell et al., 1999; Salako and Tian, 2003; Nielsen and Vigil, 2005). However cover crops do not only influence the water balance by plant water uptake. Colla et al. (2000) showed that cover crops increase both water holding capacity and soil permeability. Folorunso et al. (1992), Martens and Frankenberger (1992) and Joyce et al. (2002) found improved rainfall infiltration in cover cropped fields compared to fallow. Villalobos and Fereres (1990) and Wagner-Riddle (1997) showed the reduction of soil evaporation due to ground cover by crop canopies resulting even in higher soil water contents in the uppermost soil layer.

Islam et al. (2006) presented results of a modelling analysis of cover crop influences on water balance variables showing that cover crop actual evapotranspiration generally exceeded soil evaporation from fallow independent of water table depth and climatic characteristics. Management induced termination of the cover crops before senescence, however, reduced the water losses by as much as 31%. Under central European conditions, cover crops, generally planted between late July and mid September, are either frost-killed during winter or interrupted in their growth and development until spring in case of winter-perennial species. Such winter hard species are also commonly terminated before senescence in early spring by a herbicide application in March or early April of the following year.

A widely used approach to estimate water requirements of agricultural crops is the FAO 56 crop coefficient method (Allen et al., 1998). The semi-empirical FAO model provides a simple calculation of both, soil evaporation and plant transpiration, based on crop specific coefficients and a daily water balance. The crop coefficient method has been applied to estimate water use and irrigation requirements of a wide range of agricultural crops under different climatic conditions (e.g. Abdelhadi et al., 2000; Poulovassilis et al., 2001; Zhang et al., 2004; Howell et al., 2004; Kar et al., 2006). Data requirements are less than for mechanistic soil-plant-atmosphere models, hence the FAO approach could be a convenient tool to provide estimates of the water storage depletion by cover crops in the crop rotation.

Plant water extraction from the soil is related to the rooting pattern of crops. The original function proposed by Feddes et al. (1978) assumed a homogeneous distribution of transpiration over the root zone to be used in modelling of plant water uptake. Later research revealed that the depth distribution of root parameters, like root length density or root surface area density, as well as water uptake profiles frequently follow a linear or exponential decrease with depth (Prasad, 1988; Vrugt et al., 2001; Hopmans and Bristow, 2002; Feddes and Raats, 2004).

Turner (1979) and Blum (1996) among others discussed mechanisms of water stress compensation from deeper wet soil layers when water uptake is reduced due to dry conditions in the upper part of the soil profile. Even if root density decreases with depth, plants are able to partially or totally compensate the reduced water uptake form the upper layer by single roots in the deeper soil profile. The inclusion of water stress compensation has been shown to improve simulations of plant water extraction and actual transpiration (Li et al., 2001; Lai and Katul, 2000; Homaee et al., 2002).

The two objectives of the present study are i.) to estimate cover crop transpiration and water use efficiency using the FAO dual crop coefficient approach including both, water uptake in the root zone in relation to a measured root distribution function, and a stress compensation function integrated in the model and ii.) to analyse the amount and contribution of soil evaporation and plant transpiration in the overall water losses to the atmosphere for cover cropped fields compared to fallowing under semi-arid conditions. Comparing model estimates to actual evapotranspiration calculated from the water balance of a hydrological field measurement site, the suitability of the FAO method to obtain reasonable estimates of cover crop induced soil water depletion will be tested and the effect of different cover crop parameters on soil evaporation and the plant water uptake pattern will be discussed.

6.2 Material and methods

6.2.1 Characterization of soil properties

Table 6.1 shows selected soil properties of the study site for the two soil layers considered by the FAO 56 crop coefficient method. Z_e (0-20 cm) is the upper layer where both evaporation and transpiration occur, while z_r is the deeper layer reaching from z_e to the actual rooting depth. When root growth reaches maximum depth, z_r is 20-60 cm. Particle size distribution was determined by sieving and sedimentation analysis (ÖNORM, 2002) and converted to the FAO texture classes (FAO, 1990). Water content at field capacity and permanent wilting point were derived from retention curves obtained from field water content and water pressure head measurement data fitted to a van Genuchten type function using RETC (VanGenuchten et al., 1991). Hydraulic conductivity for the upper layer was calculated from disc infiltrometer measurements (Reynolds, 1993). Both, field retention curves and field measured hydraulic conductivity agreed well with calculations using a pedotransfer function presented by Nemes et al. (2001). For the deeper soil layer, where hydraulic conductivity was not measured in the field, we thus used the pedotransfer function based estimate for the calculation of deep percolation in the water balance. According to the world reference base for soil resources, the soil at the study site is a calcareous chernozem on loess (FAO, 1998).

Table 6.1 Soil properties.

Parameter measured	Soil Layer	
	z_e (0-20 cm)	z_r (20-60 cm)
Sand (%)	33.2	37.2
Silt (%)	51.3	48.3
Clay (%)	15.5	14.5
Textural class (FAO)	siL	L
Bulk density (g cm^{-3})	1.64	1.52
Humus content (%)	2.0	1.8
θ_{FC} at ψ = 33 kPa (cm cm^{-3})	0.26	0.25
θ_{PWP} at ψ = 1500 kPa (cm cm^{-3})	0.13	0.11
Available water (mm m^{-1})	130	140
Saturated hydraulic conductivity (cm h^{-1})	8.3	21.5

6.2.2 Plant measurements

Ground cover by the cover crops was measured four times during the growing period by image analysis of digital pictures using the software SigmaScan according to Karcher and Richardson (2005). Three digital photos were taken per plot from a height of one meter above the ground.

Plant height and total aboveground biomass were determined at the end of the cover crop vegetation period at beginning of December. Plant height measurements were done manually at 10 plants per plot. Aboveground biomass was determined as dry weight from a sample of 1m^2 per plot.

Root samples were taken using a root auger to a depth of 40 cm and subdividing the soil cylinder in three sub-samples (0-10, 10-20, 20-40 cm). Root parameters were determined by the image analysis software WinRHIZO following the working procedure proposed by Himmelbauer et al. (2004). Percent root length in the upper (0-20 cm) and deeper soil layer (20-60 cm) were calculated from the area under a curve fitted through the three data points to a maximum rooting depth of 60 cm.

6.2.3 Soil moisture measurements and water balance calculation

For continuous measurements of volumetric soil water content, capacitance sensors (CProbe) were installed in access tubes after cover crop seeding. Measurement depths were 10, 20, 40, 60 and 90 cm, the measurement interval was 15 minutes. For the water balance calculation, data were averaged to daily values. Due to a technical problem in the radio transmission of the data between 2 and 10 December 2004 only incomplete data were available for this period. In 2005 a complete hydrological field measurement site as described by Bodner et al. (2005) was installed, providing also data on water pressure head measured by granular matrix sensors (Watermark) in the same depth as water content measurements.

The actual evapotranspiration was calculated by the water balance equation:

$$Et_{act} = P - DP - \Delta S \qquad (6.1)$$

where Et_{act} is actual evapotranspiration (mm), P is precipitation (mm), DP is deep percolation (mm) and ΔS is change in soil moisture storage (mm) to a profile depth of 90 cm. Deep percolation below 90 cm soil depth was calculated following Darcy's law

$$DP = -k_h \frac{\delta H}{\delta z} \qquad (6.2)$$

where k_h is hydraulic conductivity (mm d^{-1}) and δH/δz is the hydraulic gradient.

Because there were no erosive storm events exceeding an I_{30} of 12 mm h^{-1}, which is frequently used as threshold value in erosion calculation (e.g. Wishmeier and Smith, 1978), we neglected the runoff term for 2005.

In 2004 there was still no full hydrological measurement site installed at the experimental field, thus readings of water pressure head for the calculation of deep percolation were not available. We therefore calculated monthly effective rainfall following the USDA procedure (USDA, 1970) to determine the amount of deep percolation and runoff for the water balance. This resulted in an estimate of the sum of deep percolation and runoff of only 1.1 mm in October and of 19.4 mm in November 2004. From 1 to 10 December there was no rainfall. After the only intense rainfall of 37.8 mm on 9th November the measured increase in profile water storage was only 21.1 mm in average. Potential evapotranspiration was 0.26 mm for this day. This would result in a water loss due to runoff and deep percolation of 16.4 mm for this storm event. Thus 85 % of the monthly runoff and deep percolation resulting form the effective rainfall calculation could be attributed to this single storm event. We therefore concluded that only for this day a correction is required for deep percolation and runoff In the daily water balance. For the other rainfall events, the assumption of no runoff and deep percolation will induce only insignificant error in the water balance. This is also suggested by the water content measurements at 90 cm sensor depth showing no mayor changes except after 9th November.

6.2.4 Evapotranspiration calculations

6.2.4.1 Dual crop coefficient approach

Evapotranspiration was calculated using the FAO 56 dual crop coefficient method (Allen et al., 1998). The method follows a three step approach:

1) Potential evapotranspiration of a grass reference surface (Et_0) is calculated from climatic data measured by an automated weather station located at the experimental site using the Penman-Monteith equation.

2) The reference evapotranspiration is adjusted for the individual crops using a crop coefficient K_c .

$$Et_c = K_c Et_0 \qquad (6.3)$$

where Et_c (mm) is potential crop evapotranspiration under standard conditions, K_c (-) is the crop coefficient and Et_o (mm) is reference evapotranspiration. The dual crop coefficient approach splits the K_c factor into two separate coefficients, a basal crop coefficient for transpiration (K_{cb}) and an evaporation coefficient (K_e). Thus:

$$Et_c = (K_{cb} + K_e)Et_0 \tag{6.4}$$

3) For water limiting conditions, the coefficients of Eq. 6.4 are multiplied by reduction factors (0-1) when soil water storage in the root zone has been depleted under a threshold value that separates weather controlled constant rate from soil profile controlled falling rate evapotranspiration.

The reduction function is determined by

$$K_s = \frac{TAW - D_{r,i}}{TAW - RAW} \tag{6.5}$$

where Ks (-) is the reduction coefficient, TAW (-) is total available water (i.e. water stored in the root zone between field capacity and permanent wilting point), $D_{r,i}$ (mm) is root zone depletion (cf. Eq. 6.8) and RAW (mm) is readily available water (i.e. a user defined threshold between stage one and stage two evapotranspiration).

Thus the final equation for the actual crop evapotranspiration is:

$$Et_{c,akt} = (K_s K_{cb} + K_e)Et_0 \tag{6.6}$$

where K_s (-) is the reduction coefficient for the transpiration component.

For the evaporation component, K_e is defined as:

$$K_e = \min(K_r(K_{c\max} - K_{cb}), f_{ew} K_{c\max}) \tag{6.7}$$

where K_r (-) is the evaporation reduction coefficient, K_{cmax} (-) is a maximum evapotranspiration coefficient of wet soil being 1.2 by default, K_{cb} (-) is the basal crop coefficient for the transpiration component and f_{ew} (-) is soil fraction not covered by plants and exposed to evaporation.

The soil profile is subdivided in two layers, z_e being the upper soil layer where both, evaporation and transpiration occur, and z_r being the deeper profile layer, confined by actual rooting depth, where only plant water extraction for transpiration takes place. In order to determine water availability for evapotranspiration, root zone depletion is calculated using a daily water balance based on a simple tipping bucket approach:

$$D_{r,i} = D_{r,i-1} - P_i + ET_{c,i} + DP_i \tag{6.8}$$

where $D_{r,i}$ (mm) is root zone depletion at the end of day i, $D_{r,i-1}$ (mm) is root zone depletion at the end of the previous day i-1, P_i (mm) is precipitation on day i, $ET_{c,i}$ (mm) is actual evapotranspiration on day i and DP_i (mm) is the water loss out of the root zone by deep percolation on day i.

6.2.4.2 Estimation of basal crop coefficients

As basal crop coefficients for cover crops are not available in literature, we used a calculation procedure to estimate K_{cb} described by Allen et al. (1998). The crop coefficient curve is subdivided in three stages, an initial stage ranging from germination to 10 % ground cover ($K_{cb,ini}$) with a value of 0.15 applicable for most crops, a mid stage when crops reach maximum transpiration at a ground cover of 70-75 % ($K_{cb,mid}$) and an end value at maturity ($K_{cb,late}$). As some cover crops did not reach full ground cover, the following equation was used to estimate $K_{cb,mid}$ (Allen et al., 1998):

$$K_{cb,mid} = K_{c,\min} + (K_{cb,full} - K_{c,\min})\left(\min(1{,}2f_c, f_{ceff}{}^{\frac{1}{1+h}})\right) \tag{6.9}$$

where $K_{cb,mid}$ (-) is the crop coefficient at the stage of maximum transpiration for plants not reaching full ground cover, $K_{c,min}$ is a minimum value for evaporation of bare soil in the presence of some vegetation (0.15), $K_{cb,full}$ (-) is a plant height based estimate of the K_{cb} value for full ground cover, f_c (-) is the fraction of ground covered, f_{ceff} (-) is the fraction of ground covered or shaded by vegetation being a function of solar angle and the structure of the plant canopy and h is plant height.

Cover crops do not reach maturity as common agricultural crops, but are interrupted in their development or killed by frost during winter. A value for $K_{cb,late}$ before the end of the vegetation period was re-calculated by Eq. 6.8 based on the last measurement of ground cover.

Due to reduced ground cover in some species and for reasons of comparison with similar crops tabulated in the FAO 56 guidelines, a K_{cb} for 90 % cover was calculated using an adjustment factor according to

$$A_{cm} = 1 - \left(\frac{f_c}{f_{cdense}}\right)^{0.5} \tag{6.10}$$

where A_{cm} (-) is a dimensionless adjustment factor (0-1), f_c is fraction ground cover (-) and f_{cdense} (-) is fraction ground cover for dense vegetation (i.e. 0.90).

6.2.4.3 Root distribution and water stress compensation

The original dual crop coefficient approach does not give any special references to the distribution of root water uptake over the root zone. As the FAO approach divides the soil profile in only two layers of depth z_e and z_r, we described the water uptake pattern from each layer as equivalent to the root length fraction present in the distinct layer, while water uptake is taken as homogeneous within each layer. When rooting depth exceeds z_e, an increasing proportion equivalent to $z_r/(z_e+z_r)$ of total transpiration is attributed to the deeper layer z_r. This redistribution approaches its respective upper and lower limits in z_r and z_e equal the measured root fraction present in each layer at full plant growth.

The possibility of water stress compensation when the upper layer z_e becomes dryer than the deeper layer z_r was incorporated in the model by calculating an additional water uptake from z_r using:

$$T_{zr,stress} = \min\{(RF_{zr}K_{cb}Et_0 + RF_{ze}K_{cb}Et_0 - T_{akt,ze})K_{s,zr}, TAW - (K_{s,zr} - K_{s,ze})(TAW - RAW)\}$$

for $K_{s,zr}$>$K_{s,ze}$ and $z_r > 0$ (6.11)

where $T_{zr,stress}$ (mm) is stress compensated water uptake form z_r, RF_{zr} (-) is the amount of total transpiration extracted from the deeper layer, K_{cb} (-) is the basal crop coefficient, Et_0 (mm) is reference evapotranspiration, RF_{ze} is the fraction of water extracted from z_e, $T_{akt,ze}$ (mm) is the actual transpiration from z_e, $K_{s,zr}$ (-) is the reduction coefficient for the deeper layer, TAW (mm) is total available water in z_r, $K_{s,ze}$ (-) is the reduction coefficient for the upper layer and RAW (mm) is readily available water in z_r.

The first term in Eq. 6.11 gives the proportion of potential transpiration attributed to the deeper layer due to the root fraction in this layer. The second term accounts for an additional water uptake potential being equivalent to the proportion of potential transpiration attributed to the upper layer due to root distribution that could not be extracted because of water stress. Both terms give the total potential transpiration from the deeper layer that is multiplied by the water availability (i.e. reduction coefficient) in this layer. The minimum condition ensures that the amount of water extracted from the deeper layer does not exceed a depletion where both layers have a reduction coefficient of $K_{s,zr} = K_{s,ze}$ (i.e. the same water availability in both layers).

Equation 6.11 can be applied using any threshold value for the start of stress compensation corresponding to a certain K_s in the upper layer. Also stress compensation in the upper layer due to higher depletion in the deeper root zone could be considered, but did not occur in the present study.

Table 6.2 FAO model parameterization.

Parameter	Type	Source[a]		Value	Method
Fraction ground cover (%)	State variable	MEAS		-	Image analysis
Plant height (m)	State variable	MEAS		-	10 plants per plot
Maximum root depth (m)	Fixed parameter	EST (OBS)		0.60	Deepest upward Δψ under cover crops 2005
Root growth	State variable	EST (LIT)		-	Pearl-Verhulst growth curve
Depth evaporation layer z_e (m)	Fixed parameter	EST (OBS)		0.20	Deepest upward Δψ under fallow 2005
TAW (mm z_e^{-1} resp. mm z_r^{-1})	Fixed parameter	MEAS	z_e	26 (39[b])	From measured soil parameters (Table 1)
			z_r	42	
RAW (mm z_e^{-1} resp. mm z_r^{-1})	Fixed parameter	EST (LIT)	z_e	16	Following FAO 56 recomendations
			z_r	0.5 TAW_{zr}	

[a]*MEAS: measured, EST (OBS): estimated from field observations, EST (LIT): estimated from literature*
[b]*For soil evaporation TAW is calculated as (θ_{Fc} – 0.5 θ_{PWP})z_e (Allen et al. 1998)*

6.2.4.4 Model parameterization

Table 6.2 shows the input parameters and state variables used for the dual crop coefficient calculation procedure. Those parameters for which no direct measurements were available were derived from literature or estimated from observations at the field study site.

6.2.5 Statistical analysis

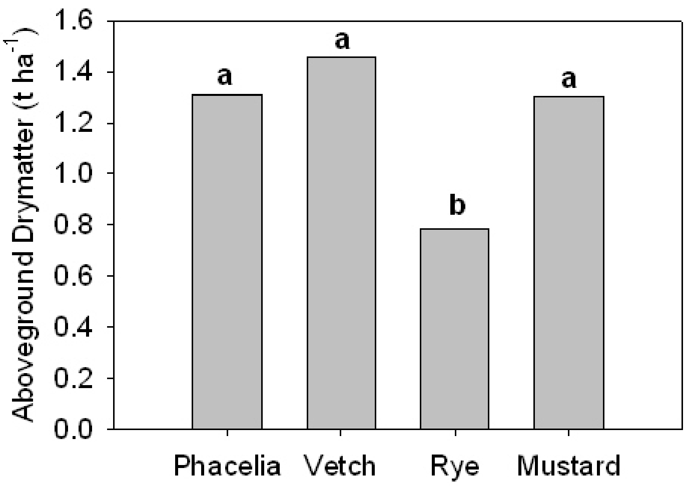
An analysis of variance was performed for the replicated measurement data using the General Linear Model (GLM) procedure of the SAS package (SAS Institute Inc., 2004). Repeated measurements of ground cover were analysed using the procedure MIXED with the option REPEATED of SAS 9.1. Data were analyzed according to the randomized complete block design. Where significant differences among treatments were identified at $p<0.05$, treatment means were compared using a Tukey test.

6.3 Results

6.3.1 Cover crop growth

Fig. 6.1 shows the aboveground dry matter of the cover crops averaged over both years. There was no significant effect of the year except for vetch. The rye cover crop had a significantly lower mean biomass growth than the other cover crop species.

Figure 6.1 Mean aboveground dry matter of cover crops *(bars with the same letter do not show significant differences for $p < 0.05$)*.



Root distribution of cover crops between the upper and lower soil layer was significantly influenced by the year (Fig. 6.2). The dry conditions in 2005 resulted in a 14.3 % higher proportion of roots in the lower soil layer compared to 2004. While relative root distribution did not differ significantly between the cover crop species, absolute root length density was highest both in the upper and lower soil layer for phacelia and lowest for vetch (figure not shown).

Fig. 6.3 shows the influence of the different growing conditions in both years on the development of ground cover of the cover crop plants. In 2004, due to dry conditions at seeding and a delayed germination, ground cover was lower until mid October compared to 2005. Lack of precipitation in autumn 2005 resulted in a peak of ground cover in mid October and a slight subsequent reduction due to leaf wilting. In 2004 cover crops continued to increase soil cover until mid November and had a significantly higher percentage of ground cover in the late stages than in 2005. When analysing species separately (data not shown), vetch was most sensitive to adverse conditions at planting in 2004 due to the highest water requirements for germination, while mustard did not show significant year effects.

Figure 6.2 Mean percentage of root length in upper and lower soil layer of cover crops *(bars with the same letter do not show significant differences for p < 0.05)***.**

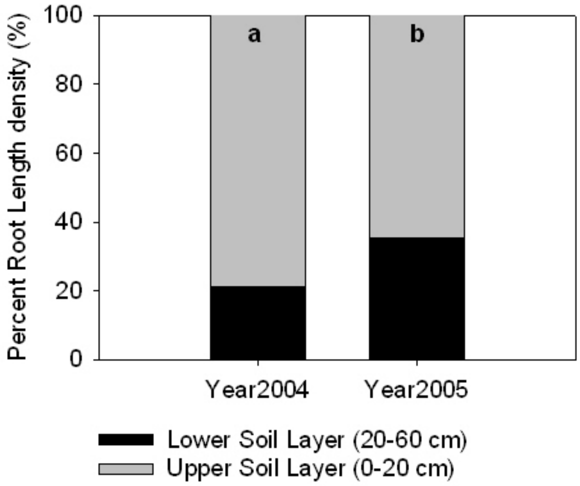
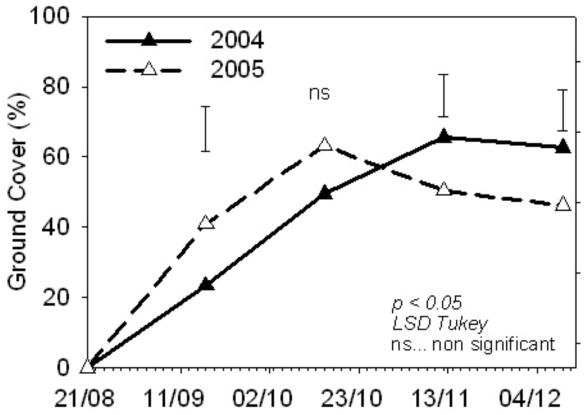


Figure 6.3 Mean percentage of ground cover of cover crops.

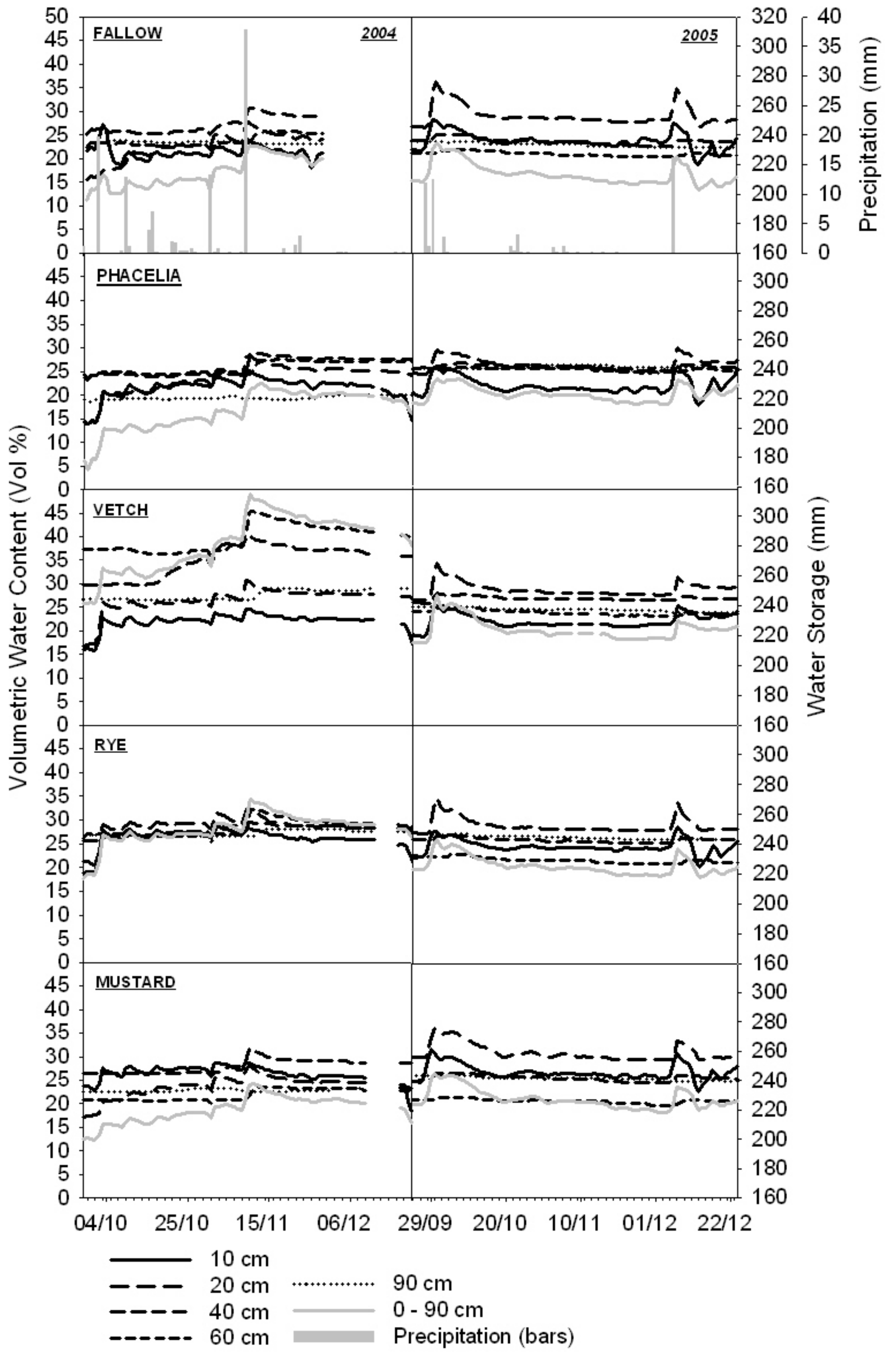


6.3.2 Soil moisture and maximum rooting depth

During the period of continuous water content measurements in 2004 a total of 110.4 mm of rain fell, while in 2005 precipitation was only 52.9 mm. The average change in water stored to a depth of 90 cm was +36.8 mm in 2004 with vetch showing the highest increase in water storage, and +10.8 mm in 2005 where a slightly higher increase was found under phacelia compared to the other crops. Measurements (Fig. 6.4) show that in 2004 an increase in water content after a rainfall event could be observed down to a depth of 60 cm, while in 2005 the low amount of precipitation showed a traceable influence on the soil water content to a maximum depth of 40 cm under fallow and of only 20 cm in the cover cropped plots. In both years the sensor in a depth of 90 cm did not indicate a change in water content except a slight increase after a high rainfall event of 37.8 mm on 9 November 2004.

Maximum rooting depth was estimated from the maximum depth of upward water fluxes in the dry autumn 2005 (cf. Table 6.2). Upward potential gradients were found to a depth of 60 cm for vetch, rye and mustard showed upward gradients to a depth of 40 cm, while measurements under phacelia suggested a maximum depth of upward fluxes of 20 cm. Considering both, root length density measurements to a depth of 40 cm and the maximum depth of upward potential gradients, 60 cm was considered a reasonable average maximum rooting depth for the cover crop water uptake.

Figure 6.4 Volumetric soil water content and water storage in the profile.



6.3.3 Crop coefficients

The calculated crop coefficients for the mid stage with maximum crop transpiration are shown in Table 6.3. Plant parameters influencing the crop coefficient calculation are soil cover and plant height and a climatic correction for relative humidity and wind speed. Both vetch and phacelia showed distinct differences in the development of percent ground cover in both years. Vetch had a significantly lower ground cover in 2004 due to adverse germination conditions, while phacelia was affected by drought in the later development stages in 2005. The $K_{cb,mid}$ values calculated for non-pristine vegetation therefore differed substantially between the two years.

When adjusted to a common ground cover of 90 %, the average difference of the calculated $K_{cb,mid}$ values of the cover crops between both years was 3.8 %. The calculated values agreed well with plants of the same botanical family and a similar habitus.

Table 6.3 Calculated mid season basal crop coefficients.

Species	GC (%)		$K_{cb,mid}$ (-)		Mean K_{cb} at 90 % GC (-)[a]	Reference K_{cb}[b]	
	2004	2005	2004	2005	Ø 2004/05	K_{cb}	Crop
Phacelia	82.2	59.7	0.85	0.67	0.90	not available	
Vetch	61.7	93.6	0.67	0.91	0.89	1.1	Legumes
Rye	43.9	59.4	0.55	0.63	0.85	0.90	Cool season turf grass
Mustard	72.6	74.0	0.83	0.85	0.96	0.95	Rapeseed

[a]*Calculated using Eq. 6.10*
[b]*from Allen et al. 1998*

6.3.4 Water balance and FAO based evapotranspiration

Figure 6.5 shows the cumulative actual evapotranspiration calculated from the water balance (Eq. 6.1) and the results obtained by using the FAO model for both years 2004 and 2005. There was good agreement between cumulative ET_{act} based on water balance calculation and the FAO model for the measurement time covering the main growing period of the cover crop plants. For mustard in both years and for rye in the dry autumn 2005, the original FAO model underestimated the total ET_{act}. However, using the new water stress compensation algorithm, we achieved a substantial improvement reducing deviations between the water balance based total ET_{act} and the model based calculations for mustard from 10.4 mm to 0.8 mm in 2004 and from 10.3 mm to 4.8 mm in 2005. For rye, the stress compensated calculation in 2005 reduced the estimation error from 12.6 mm to 1.5 mm. For the other species, the reference values of cumulative ET based on the water balance equation did not suggest any stress compensation.

6.3.5 Transpiration coefficients and water use efficiency of cover crops

Based on the overall FAO model estimates from seeding until the end of the cover crop vegetation period in mid December, cumulative plant transpiration was related to total biomass dry matter of the cover crops. Table 6.4 shows the transpiration coefficients and water use efficiencies of the cover crops for both years and their mean values. The parameters relating biomass to plant water use, i.e. transpiration coefficients and their inverse, water use efficiency, are no physiologically fixed parameters of plants as outlined by Ehlers et al. (2003), but are related particularly to the climatic conditions of plant growth as saturation vapour pressure deficit or potential evapotranspiration. In 2004 the saturation vapour pressure deficit (Δe) was slightly higher during the cover crop growing season compared to 2005. This is consistent with higher transpiration coefficients and lower water use efficiencies in 2004, except for rye where water stress compensation was suggested by the measurements in 2005. Phacelia and vetch had a more efficient water use in both years compared to rye and mustard.

Figure 6.5 Cumulative evapotranspiration from water balance calculation and the FAO model.

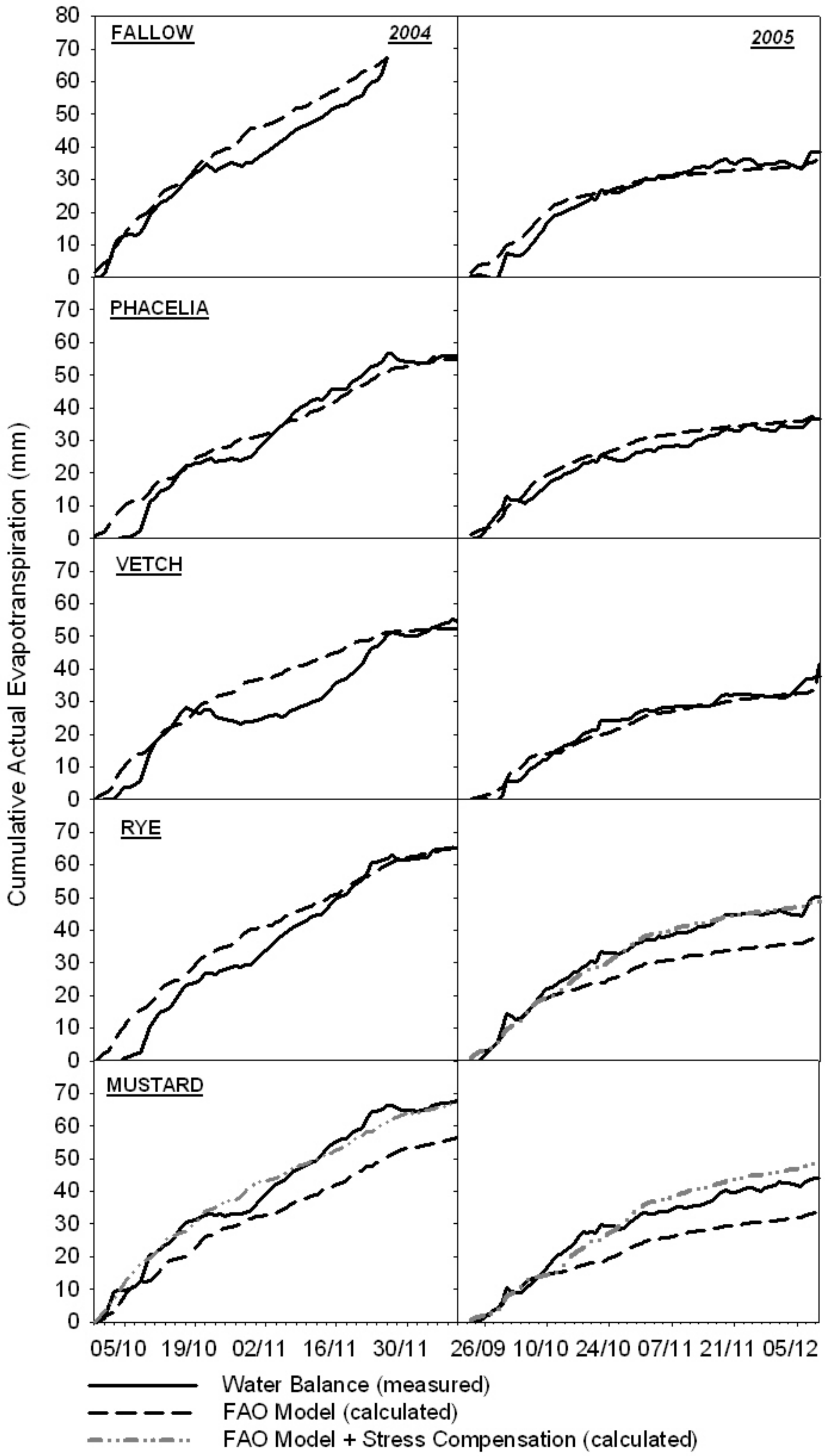


Table 6.4 Saturation vapour pressure deficits, transpiration coefficients (TC) and water use efficiencies (WUE) of the cover crops.

Year	Δ e (Pa)	Parameter	Phacelia	Vetch	Rye	Mustard
2004	295.3	TC (mm kg^{-1})	258.4	219.5	321.9	419.3
		WUE (g mm^{-1})	3.87	4.56	3.11	2.38
2005	250.2	TC (mm kg^{-1})	159.4	163.7	389.0	315.4
		WUE (g mm^{-1})	6.27	6.11	2.57	3.17
Mean	272.8	TC (mm kg^{-1})	208.9	191.6	355.5	367.3
		WUE (g mm^{-1})	5.07	5.33	2.84	2.78

6.4 Discussion

During two years the evapotranspiration of a cover cropped field was investigated. The two years differed substantially in the climatic conditions for plant growth. Due to its high seed weight compared to the other cover crop species, vetch was most susceptible to drought at and after seeding leading to a delayed germination in 2004. Both, ground cover and root distribution, are plant parameters influencing evapotranspiration and being highly susceptible to yearly differences in climatic growing conditions.

The mid season crop coefficients of the autumn grown cover crops were generally low even if corrected for full ground cover. Compared to tabulated values of similar crops, deviations could be a result of the different atmospheric conditions for the main crop K_{cb}-coefficients and those of autumn and winter grown cover crops. In the case of vetch, difference between the calculated $K_{cb,mid}$ and the average value tabulated for legumes are probably also influenced by the relatively small plant height of the vetch plants (Ø 2004-2005: 12.2 cm). For mustard and rapeseed, being particularly similar in their habitus, tabulated and calculated values agreed best.

The FAO 56 dual crop coefficient method with the calculated crop coefficients was used to estimate the actual evapotranspiration of the four cover crops compared to fallow. The total water losses to the atmosphere during the cover crop growing period ranged from 88.9 mm for vetch in 2005 to 133.7 mm for fallow in 2004. For analysing the structure of evapotranspiration, table 6.5 shows the amount of the single components contributing to the overall evapotranspiration calculated by the model. In 2004, 63 % (mustard) to 93 % (vetch) of the total plant water uptake occurred from the upper layer to a depth of 20 cm, while in 2005 plants extracted only between 32 % (mustard) to 55 % (phacelia) of their total water use from the upper 20 cm due to frequent water stress occurring during the main growing period of the crops.

The maximum share of cover crop transpiration towards total evapotranspiration was found for mustard with 60 % in 2004, while on average cover crop transpiration only accounted for 33 % of the total water losses to the atmosphere. This result reflects the reduced evaporative power of the atmosphere with a mean vapour pressure deficit of 0.20 kPa when cover crops had their most intensive biomass growth between mid September to mid November. In average this was 58 % less than the vapour pressure deficit between cover crop seeding and early juvenile development in late summer, where soil evaporation is dominant over plant transpiration. A fast and effective coverage of the soil by the growing crops reduced soil evaporation resulting in higher water availability for plant water uptake from the upper layer as observed particularly for vetch in 2005. Rye performed worst in reducing evaporative losses from the soil in both years due to limited soil coverage.

The cover cropped plots exceeded fallow in water losses to the atmosphere between 3.5 mm to 14.8 mm in the dry year of 2005 with the exception of vetch having a slightly lower total evapotranspiration than fallow. In 2004, on the contrary, fallow had the highest total evapotranspiration. Most water losses took place from the upper layer where both, evaporation and transpiration occurred. Plant water uptake thus was mainly a redistribution from soil evaporation to plant transpiration. This explains why we found only minor differences in measured soil water storage changes between the cover cropped and fallowed plots. As shown by Odhiambo and Bomke (2006), a lack of soil cover can even result in higher water losses in fallow compared to cover crops, particularly when frequent wetting of the soil allows unrestricted evaporation at a potential level.

Comparing water balance based evapotranspiration to the modelling results, water stress compensation from deeper soil layers is suggested for rye in 2005 and mustard in both years. For rye this could be explained by the high competition between evaporation and transpiration in the upper layer as insufficient soil cover did not reduce evaporation compared to the other species with high ground cover. In the dry year 2005, when the water reservoir in the evaporative layer was not refilled by precipitation, this resulted presumably in an increasing uptake from the deeper layers by rye. As discussed by Ritchie (1983), also transpiration efficiency may be reduced for sparse canopies due to a so called “clothesline effect” inducing a higher vapour pressure deficit for the plants.

Mustard showed a faster growth under the dry seeding conditions of 2004 with an average difference in ground cover compared to the other species of +11.9 % in mid September and +14.5 % in mid October. As root penetration is considered to be related to aboveground biomass development, model calculations for mustard led to a rooting depth of > 20 cm 16 to 29 days earlier than the other cover crops. In 2004 water stress occurred more frequently before mid September as only 24 % of the total precipitation during the cover crop vegetation period fell until this date. Thus, mustard could already compensate water shortage in the upper layers during this early stage. Kage and Ehlers (1996) consider a rapid development of the root system into depth as essential for a drought tolerant plant ideotype. In 2005 frequent water stress occurred during the main growing period and was efficiently compensated by deep profile depletion of the fully developed mustard plants.

Water balance calculations did not suggest water stress compensation with phacelia and vetch. In 2004 this result could be explained by the delayed root growth due to the adverse germination conditions as well as a low total biomass particularly for vetch (0.86 t ha^{-1}). During the main growing period between mid October and mid November sufficient rainfall refilled the soil water reservoir to account for the transpiration demand of the crops. In 2005 however the main growing period was characterized by frequent water stress and vetch had an intense biomass growth (2.06 t ha^{-1}). Water content measurements in this year show a lower average water content to a depth of 20 cm under vetch and phacelia compared to the other varieties between -0.21 cm^3 cm^{-3} to -0.51 cm^3 cm^{-3} For vetch we suppose that the reduction of soil evaporation by the fast and nearly complete ground cover (94 %), being 7.7 to 11.9 mm lower with vetch compared to the other crops, provided a higher proportion of water for transpiration from the upper layer for the vetch plants. Furthermore vetch had a very homogeneous root distribution between the upper and lower soil layer resulting in a higher proportion of water uptake from the deeper soil layer without stress compensation compared to the other species with a more pronounced decrease in root length density with depth. Phacelia developed a significantly higher root length density than the other species in the upper soil layer. This might have improved the root-soil contact and enabled a more efficient water uptake.

Allison et al. (1998) indicated an average range of transpiration coefficients for cover crops between 200 to 400 mm kg^{-1} based on research work covering different European climatic conditions. Results form our model estimates ranged from 191 mm kg^{-1} for vetch to 367 mm kg^{-1} for mustard. As mentioned by Allen et al. (1986), high plant stands particularly for non-pristine vegetation may increase transpiration water losses due to increasing water transport by turbulent wind profiles which would be consistent with mustard having highest water requirements per unit biomass.

Table 6.5 Components of cover crop evapotranspiration.

Component	2004					2005				
	Fallow	Phacelia	Vetch	Rye	Mustard	Fallow	Phacelia	Vetch	Rye	Mustard
Transpiration z_e	0	28.3	17.3	19.8	50.3	0	10.8	15.9	11.8	13.6
Transpiration z_r	0	7.9	1.3	3.6	16.0	0	8.7	17.8	8.5	11.7
Transpiration z_r + stress compensation	0	-	-	-	29.3	0	-	-	20.9	28.6
∑ Transpiration	0	36.2	18.6	23.4	66.3 (79.6)[a]	0	19.5	33.7	20.3 (32.7)	25.3 (42.2)
Soil Evaporation	133.7	71.8	81.0	102.4	53.0	93.7	77.7	55.8	75.8	63.5
∑ Evapotranspiration	133.7	108.0	99.6	125.8	119.3 (132.6)	93.7	97.2	89.5	96.1 (108.5)	88.8 (105.7)

[a]*Numbers in brackets indicate the stress compensated transpiration component in the summation term.*

6.5 Conclusion

Our study showed the use of the FAO 56 dual crop coefficient method for estimating evapotranspiration of cover crops and analysing the structure of evapotranspiration of cover cropped fields. Cover crop influences on the water balance must not be reduced to transpiration losses, but have to consider reduced evaporative losses from the soil and enhanced infiltration. We showed clearly that even for the period of cover crop growth during late summer and autumn, cover crop water extraction from the soil will not necessarily exceed unproductive losses from fallow. For the period of highest evaporative demand of the atmosphere during later summer, cover crops do not have a high water uptake yet. A fast development of soil cover by the growing plants can reduce efficiently soil evaporation and redistribute available water to plant water use. The period of maximum cover crop transpiration, when plants have reached full ground cover between mid and end October, is characterized by a decreasing evaporative demand of the atmosphere.

The distribution of rainfall during the cover crop growing period is a decisive factor for cover crop induced soil water depletion. Favourable conditions for germination and early development with water shortage in the main growing period will result in soil water depletion of deeper soil layers exceeding soil evaporation of a fallowed field. An even rainfall distribution over the growing period, refilling the water reservoir in the upper layer, will lead to a similar amount of evapotranspiration for fallow and cover crops as water losses are concentrated to the upper layers where both plant transpiration and soil evaporation take place in response to the evaporative demand of the atmosphere. Our study suggests a more detailed analysis of ground cover effects of cover crops on the redistribution of evaporative water losses between soil evaporation and plant transpiration that would require models with a higher depth discretization of the soil profile.

A proper estimation of water uptake particularly in dry environments should consider mechanisms of water stress compensation from deeper layers in case of water shortage in the upper parts of the soil. We suggested a simple stress compensation function that could be easily integrated in model calculations and is flexible in defining a soil water depletion threshold value for stress compensation. A mayor requirement for further research of plant water uptake in water limiting conditions is a proper understanding of the interactions between plant, particularly root system characteristics and environmental variables to define crop specific conditions for the onset of water stress compensation.

6.6 Literature

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7 *Characterization of near saturated hydraulic properties along a cover cropped slope using a tension disc infiltrometer*

Abstract

Agro-environmental instruments like cover cropping can contribute to stabilize and improve soil structure related hydraulic properties. This study evaluates the influence of different cover crops during autumn and winter compared to bare soil on near saturated hydraulic properties and analyses the impact of plant induced hydraulic property effects compared to the natural variability in space and time. Four cover crops and a fallow treatment are sown after the harvest of a barley main crop on a hill slope with silty loam soil in the semi-arid area of Eastern Austria. Infiltration measurements are performed over two years during full cover crop growth before winter and in early spring before seed bed preparation for the subsequent main crop. Steady state infiltration rate is measured at -15, -8 and -2 cm as well as for 0 cm pressure head in the second year and evaluated for the influence of the soil cover treatments, the seasonal changes over winter and the topographic position along the slope. Hydraulic conductivity, flow weighted mean pore radius and effective macroporosity are calculated from the measurements. The results show that the topographic effect is most important for the sorptive number while the temporal effects have highest influence on hydraulic conductivity. The soil cover management effect is less than the natural variability, and accounts for a maximum of 10.4 % of the total variability at saturation. Hydraulic conductivity increases towards spring and is highest at the toeslope. When hydraulic conductivity values and pore radius are high in autumn, a general tendency to less increase or even a decrease over winter has been found. Approaching saturation, bare soil shows a tendency to highest conductivity and largest pore size indicating a high amount of climatic induced fissures and shrinking cracks that are however less stable over winter. Using a flow weighted pore radius instead of a constant capillary-rise based estimate, the over-winter decrease of the radius of the largest pores is compensated by a substantial increase in pore number resulting in 44 to 48 % higher effective macroporosity towards spring. The study suggests a dominant natural variability in near saturated hydraulic properties over the effects of soil cover management. A more equilibrated micro climate at the surface soil under plant covers however tends to reduce both, climate induced structure formation and degradation in the range of largest macropores.

7.1 Introduction

Soil structure is recognized as a fundamental soil quality indicator to be considered in sustainable soil management strategies (European Commission, 2002). An increasing probability of extreme weather events like intense erosive storms (Christensen and Christensen, 2003; Seiberth et al., 2007) requires a particular focus on structure related water transmission properties to avoid runoff and soil erosion. While infiltration is dominated by unsaturated hydraulic conductivity during the first part of a storm, downward water flow increasingly depends on conductivity close to saturation related to structural macroporosity for higher cumulative rates of rainfall (Edwards et al., 1988).

Cover cropping is a commonly used agro-environmental practice in soil protection and soil fertility management. Kabir and Koide (2002) and Liu et al. (2005) found an improved stability of soil aggregates and higher aggregate mean weight diameters in cover cropped fields. The permanent cover of the soil surface furthermore protects soil aggregates from the energy of the impact of rain drops and prevents surface sealing (Ramos et al., 2000). Folorunso et al. (1992), Martens and Frankenberger (1992) and Joyce et al. (2002) found improved rainfall infiltration in cover cropped plots compared to a fallow rotation. Colla et al. (2000) showed that cover crops could increase both, water holding capacity and soil permeability.

The results of Messing and Jarvis (1993), Angulo-Jaramillo et al. (1997), Coutadeur et al. (2002), Klik et al. (2004) and Fuentes et al. (2004) among others showed that structure related soil properties are subjected to a high temporal and spatial variability at different time scales ranging from a few hours as immediate consequence of a rainfall event, to seasonal changes due to climatic conditions, agricultural activities and plant growth. Land use changes induce long term variation by adaptation of soil conditions to a new equilibrium state (Schwartz et al., 2000; Bodhinayake and Si, 2004; Fuentes et al. 2004).

The results of Mohanty et al. (1994), Heddadj and Gascuel-Odoux (1999) and Casanova et al. (2000) revealed that even slight differences in soil texture as related to topographic position may induce a significant variation of soil hydraulic properties.

Several mechanisms have been described underlying the temporal dynamics of structural porosity. The effect of climatic conditions on the near-saturated macropore range can cause both, structural degradation by the impact of raindrops resulting in a decrease of soil surface macroporosity (Rousseva et al., 2002; Ndiaye et al. 2005) as well as structure formation by swelling-shrinking and freezing-thawing cycles (e.g. Benoit, 1973; Jabro, 1996; Iwata and Hirato, 2005). Several plant influences on the pore characteristics in the structural range have been observed. Plant roots can directly influence the pore system of the rhizosphere soil through local compression, crack formation via wetting-drying cycles and biopore formation (e.g. Dexter, 1987; Young, 1998; Whalley et al., 2005). Growing plant roots can also cause a temporary reduction in water transmission by clogging of existing pores used for the penetration of the soil (Mitchell et al., 1995; Angers and Caron, 1998).

A commonly used field method to characterize near saturated hydraulic properties is tension disc infiltrometry. The measurement method as well as the derivation of different water transmission properties is described in detail by Ankeny et al. (1991), Reynolds and Elrick (1991), Ankeny (1993) and Reynolds (2000). A major advantage of disc infiltrometer measurements is that no or only minimum disturbance of the soil is necessary. Several characteristic water transmission properties can be derived form disc infiltrometer measurements to analyse soil structure dynamics like flow weighted mean pore radius (White et al., 1993; Reynolds et al., 1995) and effective macroporosity (Watson and Luxmoore, 1986; Dunn and Phillips, 1991; Bodhinayake et al., 2004). Angulo-Jaramillo et al. (2000) reviewed the methodology and applications of tension disc infiltrometry. A focus of investigations using tension disc infiltrometers has been on the impact of tillage operations and different land use (e.g. Reynolds et al., 1995; Cameira et al., 2001; Schwartz et al., 2003; Bodhinayake and Si, 2004; Lampurlanés and Cantero-Martínez, 2006).

There are still fiew experimental results analysing the possibility of near-saturated hydraulic property management by different soil covers such as mulch or living cover crops during autumn and winter. Carof et al. (2005) presented the hypothesis that soil cover could eventually result in lower hydraulic conductivity near saturation due to reduced fissuring of the soil surface protected by cover crops, while on the contrary root growth could create new pores or enlarge pre-existing pores.

The objective of this paper is to analyse cover crop impacts on water transmission properties in the structural range compared to the natural variability due to topographic position along a slope and the temporal variability during the period between full cover crop growth and the establishment of the subsequent main crop. Based on tension disc infiltrometer measurements, we will derive several hydraulic characteristics to analyse the infiltration process at the experimental site for (i) cover cropped soil compared to bare soil (ii) before winter, under the living cover crop plants, and after winter, before the establishment of the main crop, and (iii) different topographical positions along the slope. Based on our results, we will discuss factors influencing the spatial and temporal dynamics of structural porosity on a hill slope under agricultural use and the possibility of soil structure management by cover cropping.

7.2 Material and methods

7.2.1 Soil properties and soil temperature

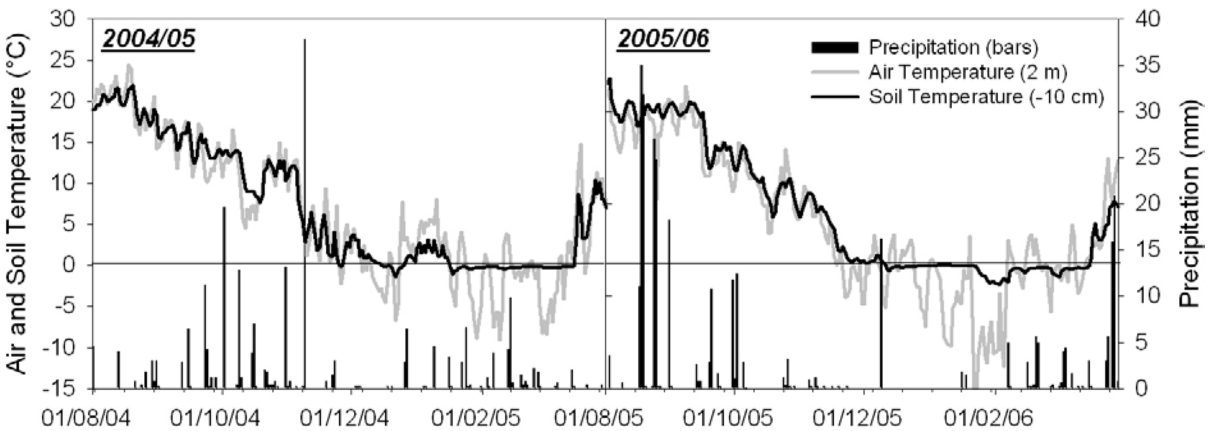
The soil at the experimental site is classified as a calcareous chernozem on loess. Table 7.1 shows soil texture, total carbon and dry bulk density in relation to the position on the slope for the upper soil layer (0-20 cm).

Table 7.1 Characteristics of the soil (0-20 cm) in relation to topographic position.

	Position		
	Summit	Midslope	Toeslope
Clay (%)	15.5	16.0	22.6
Silt (%)	51.2	51.9	44.3
Sand	33.3	32.1	33.1
Texture class (USDA)	SiL	SiL	L
C_t (%)	2.40	2.51	2.10
d_b (g cm^{-3})	1.38	1.34	1.31

Stability of soil aggregates is essential to maintain the infiltrability of the soil. Aggregate stability was determined at maximum cover crop growth at the same time as the infiltration measurements were performed. Samples were taken from the surface soil layer and the percentage of water stable aggregates was measured in the laboratory using the wet-sieving method of Kemper and Koch (1966).

Figure 7.1 Air temperature, soil temperature and precipitation at the experimental site during the cover crop season.



Soil temperature is an important parameter reflecting climatic impacts on the soil surface that can induce structure formation. In August 2005 a hydrological field measurement station was installed at the experimental site (Bodner et al., 2005). For the second year measurements of soil temperature for all treatments at 10 cm soil depth, measured in the first replication at the summit of the experimental field, were available. For 2004/05 there was still no full measurement site and data on soil temperature were only obtained for bare soil and mustard. Air and soil temperature as well as daily precipitation are shown in Figure 7.1.

7.2.2 Near-saturated hydraulic conductivity measurements

Infiltration experiments were performed using a tension disc infiltrometer with a 20 cm diameter disc membrane (Soil Measurement Systems, Tuscon, AZ). Two infiltration runs were carried out at each plot giving a total number of 30 measurements. The distance between the two subsamples within the plot was about one meter. In order to study seasonal changes in the soil hydraulic properties between autumn and spring, measurements were performed once at the end of November at full cover crop development before the non-winter hard plants were killed by frost and once at the end of March, before incorporation of the cover crops for seedbed preparation for the subsequent main crop and when the soil was sufficiently dry after winter. Steady-state infiltration rate measurements were done at the soil surface at pressure heads of -15, -8 and -2 cm following Reynolds (2000). In 2005 additionally an infiltration run was performed at saturation. After removing plant and mulch cover and building a level surface, the disc base of the infiltrometer was positioned on a thin contact layer of well sorted silica-sand. Steady-state infiltration was achieved after about 45 minutes at the lowest pressure head with time to achieve a constant infiltration rate decreasing towards saturation.

7.2.3 Calculation of soil hydraulic properties from infiltration experiments

We used the multipotential technique of Reynolds and Elrick (1991) to calculate the relation between hydraulic conductivity and water potential from the measured steady-state infiltration rates. This method is based on Wooding's solution for steady infiltration from a circular pond assuming an initially dry soil and yields estimates for the parameters in Gardner's exponential model of the hydraulic conductivity function*:*

$$K_h = K_{fs} \exp(\alpha h) \tag{7.1}$$

where K_h is the hydraulic conductivity at pressure head h, K_{fs} (cm s^{-1}) is the field-saturated hydraulic conductivity and α (cm^{-1}) is the sorptive number.

Wooding's solution for infiltration from a circular source with a constant pressure head at the soil surface, and with the unsaturated hydraulic conductivity described by Eq. 7.1, is given by:

$$Q_h = \left(\pi a^2 + \frac{a}{G_d \alpha} \right) K_h \tag{7.2}$$

where Q_h (cm^3 s^{-1}) is the steady flow rate when a constant wetting pressure head h (cm) is applied, G_d (-) is a shape factor with a value of 0.25, a (cm) is the radius of the disc, α (cm^{-1}) is the sorptive number and K_h (cm s^{-1}) is the unsaturated hydraulic conductivity at pressure head h. In Eq. 7.2 the first term represents gravitational flow while the second term represents the effects of capillary forces. Upon substitution of Eq. 7.1 into Eq. 7.2 and logarithmical transformation, the parameters α and K_{fs} can be obtained between two adjacent steady state flow rates.

Following Reynolds and Elrick (1991), in most studies (e.g. Messing and Jarvis, 1993; Šimůnek et al., 1998) Eq. 7.1 and 7.2 are applied piece-wise such that α is taken as constant between two consecutive supply pressure heads and K_h is calculated for the midpoint value at $h_{i+1/2}=(h_i+h_{i+1})/2$. Additionally the endpoints for the largest and smallest supply pressure heads are used. Thus, in our case the hydraulic conductivity curve is constructed using K_h at -15 cm, -11.5 cm, -5 cm and -2 cm. For the second year, where an additional measurement at saturation was available, we also included the value for K_{fs} in our analysis.

An important soil structure parameter derived from tension infiltrometer measurements is the flow weighted mean pore radius λ_m given by the relationship (Ankeny, 1993):

$$\lambda_m = \frac{\sigma}{\rho g \lambda_c} \tag{7.3}$$

where σ (g s^{-2}) is the surface tension of water, ρ (g cm^{-3}) is the density of water, g (cm s^{-2}) is the acceleration due to gravity and λ_c (cm) is the macroscopic capillary length which equals the inverse of α. In order to obtain estimates of λ_m for each range between the hydraulic conductivity values obtained by the procedure described above, we calculated λ_c using the following relationship (Ankeny et al., 1991):

$$\lambda_c = \frac{\Delta h (K_{hi} + K_{hi+1})/2}{(K_{hi} - K_{hi+1})} \tag{7.4}$$

The numerator in this equation represents the matrix flux potential Φ (cm^2 s^{-1}) and the denominator is the corresponding difference between the hydraulic conductivities limiting the respective range.

For the range of h_i ≤ -15 cm at the lower limit of the measured pressure heads, λ_m was estimated according to Reynolds et al. (1995) calculating a residual flux potential by rearranging Eq. 7.2 to obtain:

$$M_r = \frac{Q_{hi} - \pi a^2 K_{hi}}{Ga} \tag{7.5}$$

where Q_{hi} and K_{hi} are the steady infiltration rate and the hydraulic conductivity at h_i = -15 cm respectively. Thus λ_m for the range of h ≤ -15 cm is given by:

$$\lambda_{m,r} = \frac{\sigma K_{hi}}{\rho g M_r} \tag{7.6}$$

where $\lambda_{m,r}$ is the flow weighted mean pore radius at h ≤ -15 cm, K_{hi} is hydraulic conductivity at h_i = -15 cm and M_r is the residual flux potential (Eq. 7.5).

Based on the calculated estimates of flow weighted mean pore radii, we derived effective porosity defined as the soil volume corresponding to the pores with flowing water in a certain pressure head range (Cameira et al., 2003). Most authors have used a pore radius based on the capillary-rise equation for deriving structural porosity (e.g. Watson and Luxmoore, 1989; Dunn and Phillips, 1991). We will use both pore size estimates to highlight the role of differences in pore continuity and tortuosity between the treatments for the water-conducting macroporosity.

Effective macroporosity is obtained by calculating the pore number per unit area applying the capillary equation in conjunction to Poiseuille's equation:

$$N = \frac{8 \mu K_d}{\rho g \pi r^4} \tag{7.7}$$

where µ (g cm^{-1} s^{-1}) is the dynamic viscosity of water, ρ (g cm^{-3}) is the density of water, K_d (cm s^{-1}) is the difference between two adjacent hydraulic conductivity values and r (cm) is the pore radius (cm). Effective porosity can than be calculated as:

$$\varepsilon = N \pi r^2 \tag{7.8}$$

where N (cm^{-2}) is the number of pores per unit area. Estimates were obtained for both, macroporosity based on a flow weighted average pore radius λ_m and for a capillary based mean pore radius in the corresponding range as calculated by Dunn and Phillips (1991) applying the mean value theorem for r resulting in:

$$\overline{N} = \frac{8 \mu K_d}{\pi \rho g} \left[\int_a^b r^{-4} dr / \int_a^b dr \right] \tag{7.9}$$

and

$$\bar{\varepsilon} = \overline{N}\pi \left[\int_a^b r^2 dr \,/ \int_a^b dr \right] \qquad (7.10)$$

for Eq. 7.7 and 7.8 respectively, where a and b are the capillary based pore radii of the lower and upper limits of the integrals of each pressure head range.

7.2.4 Statistical evaluation

An analysis of variance was performed to determine if there are significant differences in the hydraulic properties between the soil cover treatments, the topographical position along the slope (summit, midslope, toeslope), the measurement date (before winter, after winter) and between the two years. All data where first checked for normality using a Kolmogorov-Smirnov test. As the data were strongly skewed, a logarithmic transformation was applied to achieve normality.

When applying an analysis of variance including repeated measurements, i.e. in our case the applied pressure head and the measurement date, the assumption of independence between the levels of the factors under consideration is not fulfilled. To perform the analysis of variance, the correlation structure of the repeated measurement factors must be defined. Following the outlines of Piepho et al. (2003, 2004), we used the procedure MIXED of the SAS software package to find an appropriate correlation model by the Akaike Information Criterion (AIC). For both repeated measures, date and pressure head, a crossed unstructured x first order autoregressive model [un x ar(1)] fit best to our data.

In case of significant differences in the Wald-F-statistic at $p < 0.05$, treatment means were compared using a two sided t-test.

Linear regression was used to analyse the influence of aggregate stability on sorptive number as well as factors influencing the rate of change between the two measurement dates.

Analysis of variance and comparison of means were done using the SAS software package Version 9.1 (SAS Institute Inc, 2004). Linear regression was calculated using SigmaPlot 8.0.

7.3 Results

7.3.1 Hydraulic conductivity

Results obtained from Wooding's analyses of the infiltration experiments are shown in Table 7.2. The values represent the geometric mean of the two subsamples per plot and the three replicates for sorptive number, the midpoint as well as the endpoint hydraulic conductivity estimates. For information we also give the midpoint value for the range between saturation and -2 cm only performed in the second year. In the further analysis however we only used the values available for both years plus the saturation estimate for 2005/06.

Table 7.2 Results from Wooding analysis of tension infiltrometer experiments.

		2004/05[a]								2005/06											
Pressure head range		Autumn				Spring				Autumn						Spring					
		-2 to -8 cm		-8 to -15 cm		-2 to -8 cm		-8 to -15 cm		0 to -2 cm		-2 to -8 cm		-8 to -15 cm		0 to -2 cm		-2 to -8 cm		-8 to -15 cm	
Fallow	α (cm^{-1})	-	0.32	0.15	-	-	0.19	0.09	-	-	0.58	-	0.25	0.11	-	-	0.45	-	0.24	0.12	-
	K_0 (cm h^{-1})	*6.48*	2.39	0.38	*0.18*	*4.90*	3.02	0.86	*0.56*	*12.71*	7.38	*3.27*	1.33	0.28	*0.19*	*15.93*	11.83	*6.07*	2.55	0.55	*0.36*
Phacelia	α (cm^{-1})	-	0.18	0.16	-	-	0.16	0.09	-	-	0.60	-	0.23	0.09	-	-	0.56	-	0.32	0.11	-
	K_0 (cm h^{-1})	*2.41*	1.39	0.43	*0.24*	*3.80*	2.50	0.92	*0.66*	*3.84*	2.48	*0.80*	0.37	0.09	*0.06*	*21.42*	12.00	*5.82*	2.10	0.34	*0.23*
Vetch	α (cm^{-1})	-	0.27	0.17	-	-	0.18	0.11	-	-	0.74	-	0.21	0.06	-	-	0.55	-	0.23	0.10	-
	K_0 (cm h^{-1})	*5.81*	2.58	0.53	*0.29*	*5.62*	3.45	1.19	*0.80*	*3.72*	1.83	*0.64*	0.29	0.06	*0.05*	*10.61*	7.49	*2.67*	1.17	0.24	*0.16*
Rye	α (cm^{-1})	-	0.22	0.15	-	-	0.18	0.09	-	-	0.79	-	0.23	0.09	-	-	0.63	-	0.26	0.10	-
	K_0 (cm h^{-1})	*3.01*	1.53	0.38	*0.20*	*4.45*	2.97	1.13	*0.82*	*6.72*	3.32	*1.02*	0.42	0.17	*0.09*	*14.19*	8.17	*3.45*	1.41	0.30	*0.20*
Mustard	α (cm^{-1})	-	0.24	0.17	-	-	0.19	0.10	-	-	0.81	-	0.21	0.07	-	-	0.59	-	0.24	0.09	-
	K_0 (cm h^{-1})	*5.43*	2.55	0.56	*0.28*	*6.45*	3.64	1.00	*0.68*	*5.63*	3.07	*0.84*	0.38	0.09	*0.06*	*10.95*	6.86	*2.61*	1.13	0.52	*0.17*

[a]*Numbers written in italic are endpoint values used in the further analysis together with the midpoint values (cf. 7.2.3) calculated from the respective pressure head ranges.*

Analysis of variance of hydraulic conductivity resulted in pressure head specific significant differences between the cover crops, the measurement dates and the position on the slope. All factors showed a significant interaction with the year. Figs. 7.2 to 7.4 show the mean hydraulic conductivity curves for i.) cover crops and bare soil, ii.) measurement dates and iii.) position along the slope.

Figure 7.2 Average hydraulic conductivity of the cover cropped plots compared to fallow. *(Bars represent least significant differences.)*

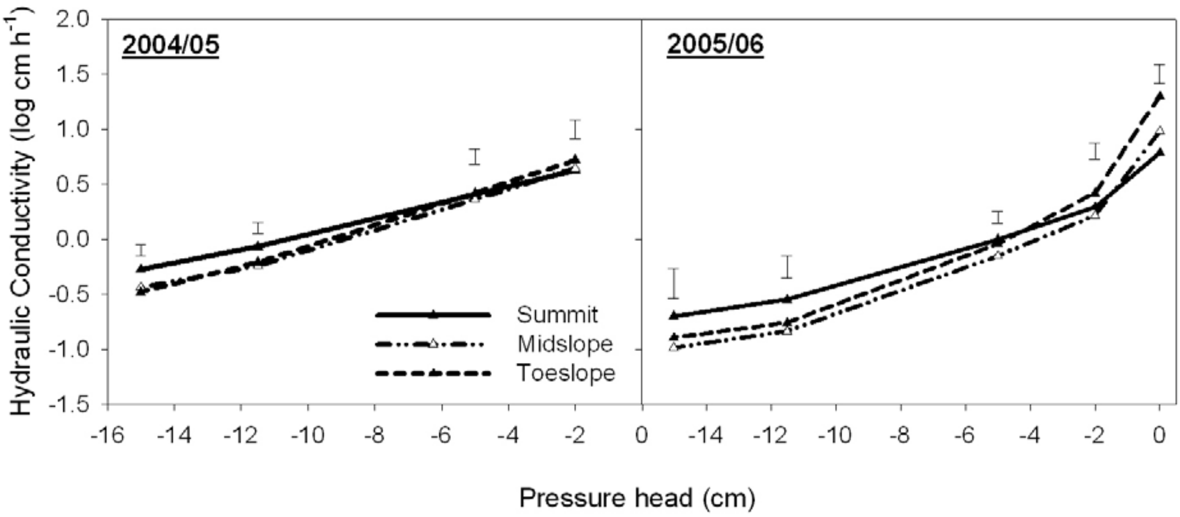


Figure 7.3 Average hydraulic conductivity at full cover crop growth before winter and before seed bed preparation for the subsequent cash crop after winter. *(Bars represent least significant differences.)*

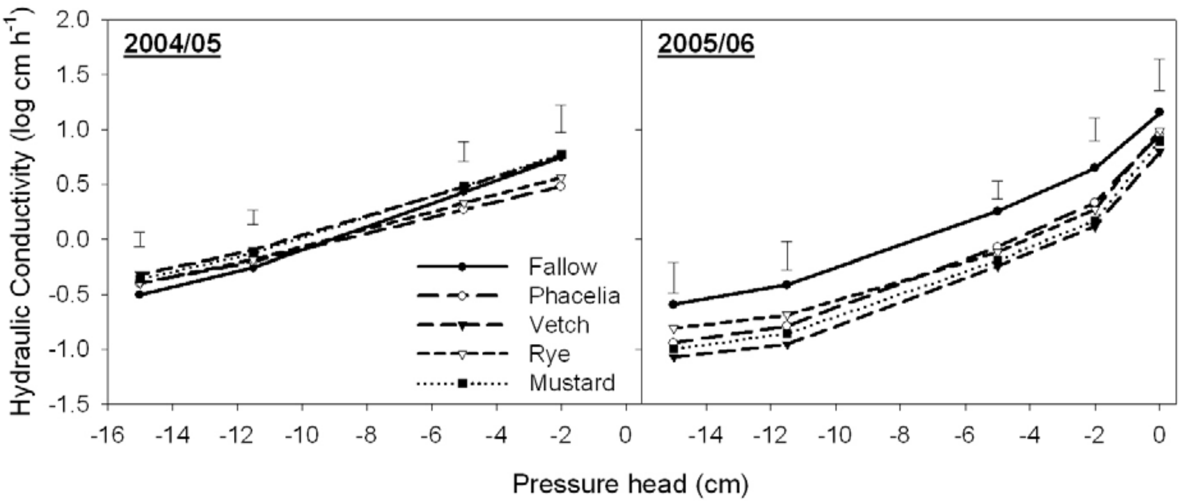
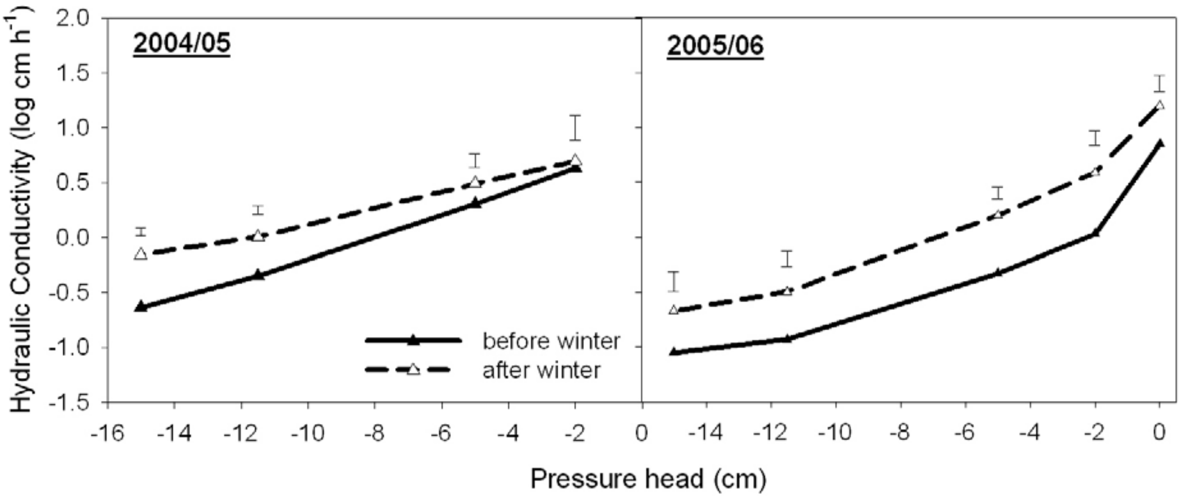


Figure 7.4 Average hydraulic conductivity along the slope. *(Bars represent least significant differences.)*



In the first year the hydraulic conductivity was higher at all pressure heads by about half order of magnitude compared to the second year. In 2004/05 fallow had the lowest conductivity value at -15 cm, showing an increasing tendency towards higher values approaching saturation. Rye and phacelia had significantly lower hydraulic conductivities at -2 cm, phacelia also at -5 cm compared to all other varieties. At the lower endpoint pressure head only vetch was significantly different from the other variants except mustard, with a hydraulic conductivity being 20 % higher in average.

In 2005/06 fallow had significantly higher conductivity values than the cover crops over the whole range of pressure heads, being 56 % above the cover cropped plots in mean. Between the cover crops there were no statistically significant differences except between rye and vetch at the lower pressure heads of -11.5 and -15 cm.

Concerning the two measurement dates, in both years the mean hydraulic conductivity was significantly higher in spring compared to autumn. In the first year only the highest pressure head measured did not show significant differences between the two dates. The average increase over winter was 0.3 orders of magnitude in 2004/05 and 0.5 orders of magnitude in 2005/06. During the first year the differences between autumn and spring increased with decreasing pressure head. In 2005/06 the highest increases occurred at -2 and -5 cm pressure head. The conductivity at saturation had the lowest increase.

Comparing the hydraulic conductivity at different topographical positions on the slope, the summit showed lowest values near saturation and highest values at -11.5 and -15 cm pressure head being significantly different from the toeslope. The toeslope on the contrary had significantly higher values at saturation.

7.3.2 Sorptive number

The α parameter in Gardner's exponential model is an indicator for the relative importance of soil structure and soil texture during the infiltration process. The analysis of variance did not reveal a significant influence of soil cover. Again differences between the years were highly significant. Also the measurement date and the position along the slope had significant influence on the sorptive number. Fig. 7.5 and 7.6 show the means for the measurement ranges for both years as influenced by the seasonal and the topographic effect.

In 2004/05 α decreased significantly towards spring for both measurement ranges, while in 2005/06 α only for the measurement range nearest to saturation between 0 and -2 cm decreased significantly. For the lower ranges no significant differences were found.

Concerning the influence of the topographic position, there was a clear tendency towards increasing values from the summit towards the toeslope in both years, particularly for heads approaching saturation. The toeslope values were significantly higher for all measurement ranges compared to the midslope and the summit, while the latter tended to equilibrate at more negative pressure heads.

Figure 7.5 Average sorptive number at full cover crop growth before winter and before seed bed preparation for the subsequent cash crop after winter. *(Bars with the same letter are not different statistically at $p < 0.05$.)*

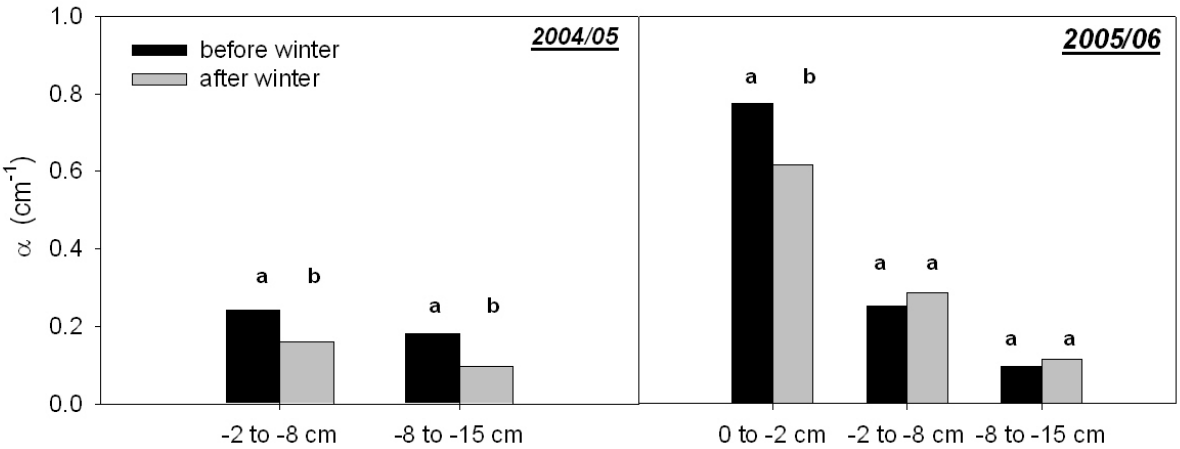
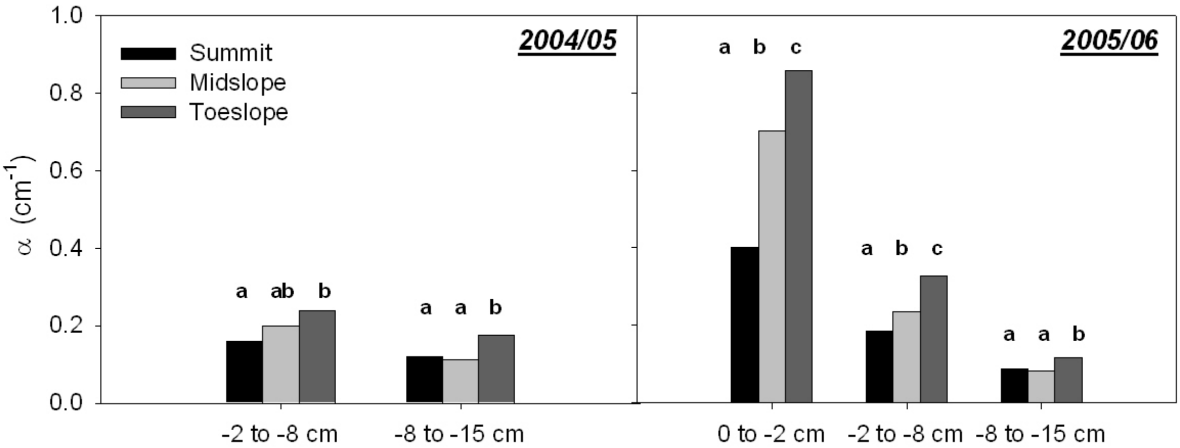


Figure 7.6 Average sorptive number along the slope. *(Bars with the same letter are not different statistically at $p < 0.05$.)*



7.3.3 Flow weighted mean pore radius and pore number

Table 7.3 compares the average value of the flow weighted mean pore radius (λ_m) with mean pore radii (r_{mean}) according to Dunn and Phillips (1991) and maximum pore radii (r_{max}) calculated by the capillary-rise equation for the respective pressure head ranges. Upper limit values for saturation are not defined for capillary based measures. Depending on the lower limit assumed for the range $h \leq -15$ cm, the Dunn and Phillips approach would result in a very small mean pore radius, giving a very high pore number and effective porosity necessary for conducting the measured infiltration flux. The flow weighted mean pore radius estimates however suggest that for increasingly lower pressure head ranges, water flow predominantly passes through pores with a radius at the upper limit of the range rather than through a mean value and λ_m approaches r_{max}, rather than r_{mean}. For a reasonable comparison of effective porosity for the range ≤ -15 cm we therefore used the upper limit capillary radius instead of a mean value as this would require an arbitrary assumption on a lower limit.

Table 7.3 Flow weighted mean pore radius, mean and maximum pore radius.

Pressure head range	λ_m	r_{c1}[a]	r_{c2}[b]	r_{max}[c]
		mm		
0 to -2 cm	0.45 (0.12)[d]	-	-	-
-2 to -5 cm	0.17 (0.05)	0.44	0.54	0.74
-5 to -11.5 cm	0.15 (0.04)	0.19	0.22	0.30
-11.5 to -15 cm	0.10 (0.04)	0.11	0.11	0.13
≤ -15 cm	0.09 (0.04)	-	-	0.10

[a]*Calculated from Eq. 7.9 (Dunn and Phillips, 1991)*
[b]*Calculated from Eq. 7.10 (Dunn and Phillips, 1991)*
[c]*Calculated from capillary-rise equation*
[d]*Numbers in brackets are standard deviations*

Tables 7.4 and 7.5 show the results of the calculated flow weighted parameters for both, the average values for the two measurement dates and for the position on the slope. The year effect was significant, while no significant difference was found between the cover treatments. Particularly pore number is a soil property with very high spatial variability. Being related to the inverse of the fourth power of the pore radius (Eq. 7.7), slight differences in radius result in substantial changes in the pore number.

In 2004/05 the flow weighted mean pore radius showed a significant decrease between autumn and spring, while in the second year, only the largest pores between 0 and -2 cm pressure head decreased, while there were no significant differences in the other ranges. The increase in hydraulic conductivity between the two dates (cf. Fig. 7.3) together with decreases or non significant changes of the mean radius of water conducting pores results in a substantially higher pore number in spring compared to autumn. Also in the second year, there was a general autumn-to-spring increase in pore number in all pressure head ranges, which however was statistically significant only in the ranges nearest to saturation.

The flow weighted pore radius was generally higher at the toeslope in both years, while the number of pores had a decreasing tendency between the summit and the toeslope. Higher hydraulic conductivities at the toeslope for pressure heads near saturation (cf. Fig. 7.4) are thus related to a significantly higher pore radius, while the higher conductivities at the summit at low pressure heads are explained by the significantly higher number in pores with a small flow weighted radius.

Although we used Eq. 7.4 to calculate λ_m within the pressure head ranges of the mid- and endpoint values determined on the hydraulic conductivity curve, the similarity to the spatial and temporal behaviour of the sorptive number can be seen clearly.

Table 7.4 Flow weighted mean pore radius and number of λ_m-pores per m^2 for autumn and spring[a].

2004/05	Pressure head range: 0 to -2 cm		-2 to -5 cm		-5 to -11.5 cm		-11.5 to -15 cm		≤ -15 cm	
	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring	Autumn	Spring
R_0 (mm)	-	-	0.17*a*	0.11*b*	0.14*a*	0.11*b*	0.13*a*	0.08*b*	0.12*a*	0.08*b*
N_0 (m^{-2})	-	-	1816*a*	8572*b*	2778*a*	9076*b*	508*a*	6563*b*	782*a*	15076*b*
2005/06										
R_0 (mm)	0.48*a*	0.39*b*	0.19*a*	0.20*a*	0.14*a*	0.15*a*	0.08*a*	0.10*a*	0.06*a*	0.07*a*
N_0 (m^{-2})	61*a*	304*b*	332*a*	993*b*	653*a*	837*a*	4473*a*	6426*a*	3560*a*	5258*a*

[a]*Values with the same letter within a pressure head range are not significantly different ($p < 0.05$)*

Table 7.5 Flow weighted mean pore radius and number of λ_m-pores per m^2 for the position along the slope[a].

2004/05	Pressure head range: 0 to -2 cm			-2 to -5 cm			-5 to -11.5 cm			-11.5 to -15 cm			≤ -15 cm		
	Summit	Mid	Toe	Summit	Mid	Toe	Summit	Mid	Toe	Summit	Mid	Toe	Summit	Mid	Toe
R_0 (mm)	-	-	-	0.12*a*	0.15*ab*	0.16*b*	0.11*a*	0.13*a*	0.14*a*	0.09*a*	0.09*a*	0.12*b*	0.08*a*	0.09*a*	0.12*b*
N_0 (m^{-2})	-	-	-	6158*a*	3270*a*	3050*a*	7952*a*	3876*a*	4106*a*	3102*a*	2195*a*	894*b*	7756*a*	4650*a*	1122*b*
2005/06															
R_0 (mm)	0.33*a*	0.49*b*	0.51*b*	0.16*a*	0.20*ab*	0.24*b*	0.13*a*	0.15*a*	0.16*a*	0.07*a*	0.07*a*	0.11*b*	0.07*ab*	0.06*a*	0.08*b*
N_0 (m^{-2})	209*a*	84*b*	144*ab*	1085*a*	461*b*	378*b*	1856*a*	579*b*	353*b*	9586*a*	7140*a*	2251*b*	7314*a*	6935*a*	1597*b*

[a]*Values with the same letter within a pressure head range are not significantly different ($p < 0.05$)*

7.3.4 Effective macroporosity

Tables 7.6 to 7.8 show means of effective macroporosity for the soil cover, measurement date and topographical position where analysis of variance indicated significant differences between both, the flow weighted pore radii based calculation and the capillary-rise based approach. Statistical differences for the values calculated according to Dunn and Phillips (1991) correspond to the results obtained for hydraulic conductivity, as pore radius is a constant parameter in the calculation procedure (Eq. 7.9 and 7.10).

Due to the higher average pore radius estimated by the Dunn and Phillips method, effective macroporosity generally is less for the capillary based compared to the flow weighted calculation procedure. The highest average difference of -79 % occurred in the range between -2 to -5 cm pressure head as the differences between the two pore size estimates tended to increase towards saturation.

In 2004/05 differences in effective macroporosity induced by soil cover, and based on the flow weighted pore radius, were not significant, while in 2005/06 bare soil showed significantly higher values in the ranges between 0 and -11.5 cm, while the smaller pore ranges did not differ significantly (Tab. 7.6).

Effective macroporosity generally increased between autumn and spring (Tab. 7.7) when using the flow weighted pore estimate. When assuming mean capillary pore radii, in 2004/05 there was a non-significant decrease in the range between -2 and -5 cm. During the first year there was a trend to a higher increase in the low pressure head ranges over winter. This is in agreement with the observation of a shift in the relative contribution to hydraulic conductivity towards the smaller pressure head range with a simultaneous decrease of the radii of water conducting pores. In 2005/06 highest macroporosity increase was found near saturation from 0 to -5 cm. For the range between -2 and -5 cm this is related to the high increase in hydraulic conductivity as the pore radius did not change significantly, while there was less increase over winter in hydraulic conductivity between 0 and -2 cm and the result reflects the significant decrease in the radius of water conducting pores. Differences between the flow-based and the capillary-rise based estimates reveal such changes over winter of pore radius in the flow weighted calculation. A reduction of pore radius, as found in 2004/05 as well as for the range of 0 to -2 cm in 2005/06, requires a significantly higher effective porosity increase between autumn and spring to account for the same water flow. The slightly increased pore radii below -2 cm pressure head in spring 2006 on the contrary resulted in between 18 % to 87 % less effective porosity increase over winter, compared with an assumed constant pore radius.

Based on the of λ_m values the slope summit had the highest total effective macroporosity in both years. Only closest to saturation, i.e. between 0 and -2 cm in 2005/06, the significantly higher pore radii at the toeslope were related to a higher effective structural porosity. The contribution of the porosity in the range closest to saturation to the total effective structural porosity is always higher at the toeslope than on the summit. The differences are particularly high in the range between 0 to -2 cm that accounts for as much as 37 % of total porosity at the toeslope and only 14 % at the summit. On the contrary, effective porosity in the range ≤ -15 cm pressure head accounts for 21 % of total porosity at the summit, 20 % at the midslope and only 10 % at the toeslope in average over both years. For a constant mean pore radius, the higher hydraulic conductivity measured at the toeslope near saturation suggests a significantly higher effective porosity towards saturation, while the summit is highest in porosity for the lower pressure heads.

Table 7.6 Soil macroporosity for flow weighted mean pore radius and mean capillary radius[a].

	Fallow		Phacelia		Vetch		Rye		Mustard	
2004/05					$cm^3\ cm^{-3}$					
	ε_{flow}	$\varepsilon_{capillary}$	ε_{flow}	$\varepsilon_{capillary}$	ε_{flow}	$\varepsilon_{capillary}$	ε_{flow}	$\varepsilon_{capillary}$	ε_{flow}	$\varepsilon_{capillary}$
-2 to -5 cm	0.0241[b]	0.0048*a*	0.0193	0.0020*b*	0.0273	0.0046*a*	0.0215	0.0026*b*	0.0273	0.0049*a*
-5 to -11.5 cm	0.0228	0.0187*a*	0.0221	0.0111*b*	0.0297	0.0192*a*	0.0238	0.0130*ab*	0.0282	0.0204*a*
11.5 to -15 cm	0.0042	0.0044*a*	0.0061	0.0041*a*	0.0067	0.0057*a*	0.0060	0.0044*a*	0.0061	0.0055*a*
≤ -15 cm	0.0087	0.0072*a*	0.0125	0.0092*ab*	0.0099	0.0110*b*	0.0104	0.0092*ab*	0.0086	0.0101*ab*
2005/06										
0 to -2 cm	0.0164*a*	-	0.0084*ab*	-	0.0051*b*	-	0.0076*b*	-	0.0062*b*	-
-2 to -5 cm	0.0149*a*	0.0044*a*	0.0069*b*	0.0022*b*	0.0047*b*	0.0013*b*	0.0060*b*	0.0019*b*	0.0052*b*	0.0014*b*
-5 to -11.5 cm	0.0109*a*	0.0127*a*	0.0036*b*	0.0063*c*	0.0039*b*	0.0042b*c*	0.0048*b*	0.0032*b*	0.0040*b*	0.0046*bc*
11.5 to -15 cm	0.0101a	0.0025*a*	0.0076*a*	0.0009*bc*	0.0105*a*	0.0006*c*	0.0127*a*	0.0015*ab*	0.0116*a*	0.0008*c*
≤ -15 cm	0.0078*a*	0.0060*a*	0.0047*a*	0.0027*b*	0.0074*a*	0.0020*b*	0.0059*a*	0.0027*b*	0.0060*a*	0.0024*b*

[a]*Values with the same letter within a pressure head range and a calculation method are not significantly different (p < 0.05)*
[b]*Due to insignificant difference according to the analysis of variance, no comparison of means was done.*

Table 7.7 Soil macroporosity calculated from flow weighted mean pore radius and mean capillary radius in autumn and spring[a].

2004/05	Autumn ($cm^3\ cm^{-3}$)		Spring ($cm^3\ cm^{-3}$)	
	ε_{flow}	$\varepsilon_{capillary}$	ε_{flow}	$\varepsilon_{capillary}$
-2 to -5 cm	0.0169*a*	0.0039*a*	0.0330*b*	0.0032*a*
-5 to -11.5 cm	0.0175*a*	0.0135*a*	0.0359*b*	0.0178*a*
11.5 to -15 cm	0.0028*a*	0.0040*a*	0.0120*b*	0.0057*b*
≤ -15 cm	0.0039*a*	0.0055*a*	0.0286*b*	0.0160*b*
2005/06				
0 to -2 cm	0.0045*a*	-	0.0144*b*	-
-2 to -5 cm	0.0037*a*	0.0010*a*	0.0125*b*	0.0039*b*
-5 to -11.5 cm	0.0041*a*	0.0027*a*	0.0058*a*	0.0113*b*
11.5 to -15 cm	0.0078*a*	0.0006*a*	0.0136*b*	0.0019*b*
≤ -15 cm	0.0043*a*	0.0017*a*	0.0090*b*	0.0049*b*

[a]*Values with the same letter within a pressure head range and a calculation method are not significantly different ($p < 0.05$)*

Table 7.8 Soil macroporosity calculated from flow weighted mean pore radius and mean capillary radius for topographical position[a].

2004/05	Summit ($cm^3\ cm^{-3}$)		Midslope ($cm^3\ cm^{-3}$)		Toeslope ($cm^3\ cm^{-3}$)	
	ε_{flow}	$\varepsilon_{capillary}$	ε_{flow}	$\varepsilon_{capillary}$	ε_{flow}	$\varepsilon_{capillary}$
-2 to -5 cm	0.0267*a*	0.0029*a*	0.0214*a*	0.0035*ab*	0.0233*a*	0.0044*b*
-5 to -11.5 cm	0.0308*a*	0.0151*a*	0.0216*a*	0.0153*a*	0.0239*a*	0.0177*a*
11.5 to -15 cm	0.0082*a*	0.0056*a*	0.0056*ab*	0.0038*b*	0.0042*b*	0.0051*a*
≤ -15 cm	0.0172*a*	0.0123*a*	0.0110*b*	0.0084*b*	0.0052*c*	0.0077*b*
2005/06						
0 to -2 cm	0.0070*ab*	-	0.0062*a*	-	0.0119*b*	-
-2 to -5 cm	0.0085*a*	0.0017*a*	0.0055*a*	0.0016*a*	0.0068a	0.0030*b*
-5 to -11.5 cm	0.0094*a*	0.0065*a*	0.0041*b*	0.0051*a*	0.0030b	0.0051*a*
11.5 to -15 cm	0.0145*a*	0.0015*a*	0.0110*ab*	0.0008*b*	0.0069b	0.0012*ab*
≤ -15 cm	0.0102*a*	0.0046*a*	0.0072*a*	0.0024*b*	0.0033b	0.0022*b*

[a]*Values with the same letter within a pressure head range and a calculation method are not significantly different ($p < 0.05$)*

7.4 Discussion

7.4.1 Factors influencing near saturated hydraulic properties

We measured steady infiltration rates over two years on a cover cropped silty loam soil compared to fallow using a tension disc infiltrometer in order to determine the importance for near-saturated hydraulic properties of temporal variability, variability along the slope and different soil cover treatments. Hydraulic conductivity curves were derived from the infiltration experiments based on Wooding's solution for steady infiltration flux from a circular pond. Based on the parameters obtained from the measured infiltration, flow weighted mean pore radius and pore number per unit area were calculated in order to obtain an estimate for effective structural porosity of the soil.

Using a mixed model based analysis of variance, the influence of the factors year, measurement time, topographical position and soil cover on the overall variance was evaluated. In the first two years of cover cropping, the management effect of different soil covers was less important than the temporal variability due to year and season as well as the spatial variability along the slope. The contribution to the total variance of the main effects, analysed separately for each pressure head and head measurement range respectively, is shown in Table 7.9 for the parameters obtained from Wooding's solution of measured infiltration.

Table 7.9 Contributions (%) to the total variance of the main determinant parameters[a].

	Hydraulic conductivity					Sorptive number		
	Pressure head					Measurement range		
	0 cm	-2 cm	-5 cm	-11.5 cm	-15 cm	0 to -2 cm	-2 to -8 cm	-8 to -15 cm
YEAR	-	26.1	41.7	47.1	35.1	-	9.3	16.5
DATE	*28.3*	19.5	24.9	24.8	29.9	*7.0*	4.6	7.3
POSITION	*32.3*	3.0	1.5	6.2	6.7	*56.6*	33.7	17.6
SOIL COVER	*10.4*	9.7	6.6	2.8	2.4	*7.8*	1.4	2.4

[a]*Numbers in italics indicate only one year (2005/06) measurements for the range between 0 and -2 cm pressure head*

The sorptive number α, which expresses the texture/structure influence during infiltration (Reynolds and Elrick, 1991; White et al., 1992), is most strongly influenced by the topographical position. The soil cover effect was higher for hydraulic conductivity than for sorptive number. The influence of the cover treatment on hydraulic conductivity showed an increasing tendency for the pressure head ranges approaching saturation. The temporal effect of measurement date was highest for both, sorptive number and hydraulic conductivity, at the lowest pressure head sequence. For hydraulic conductivity, the year effect was the main contributor to the total variance at all pressure heads.

7.4.2 Hydraulic conductivity

Soil cover can substantially change the soil energy balance and induce different behaviour concerning temperature effects and drying-wetting cycles on soil structure. Wagner-Riddle et al. (1996) found higher soil moisture in surface soils covered by rye mulch compared to bare soil due to a decrease in evaporation under residue cover. Particularly for fine-texture soils, differences in soil moisture can alter structure forming processes as found by Shiel et al.

(1988) who observed an increasing contribution of inter-aggregate shrinking fissures to macroporosity upon drying.

The significantly higher hydraulic conductivity of the bare soil in 2005/06 may result from such surface cracking induced by the dry conditions in autumn 2005 with only 11.4 mm of rain between 1 October and 1 December. In 2004 regular soil wetting by evenly distributed rainfall during the same period (total 108.6 mm) could have reduced the formation of shrinking cracks in the fallow and thus its hydraulic conductivity.

Concerning the general increase in hydraulic conductivity over winter, Qi et al. (2006) attributed this phenomenon to soil freezing, producing micro-fissures in the soil. Based on a simulation study, Flerchinger et al. (2003) showed deeper frost penetration in a bare soil compared to a surface with high residue cover.

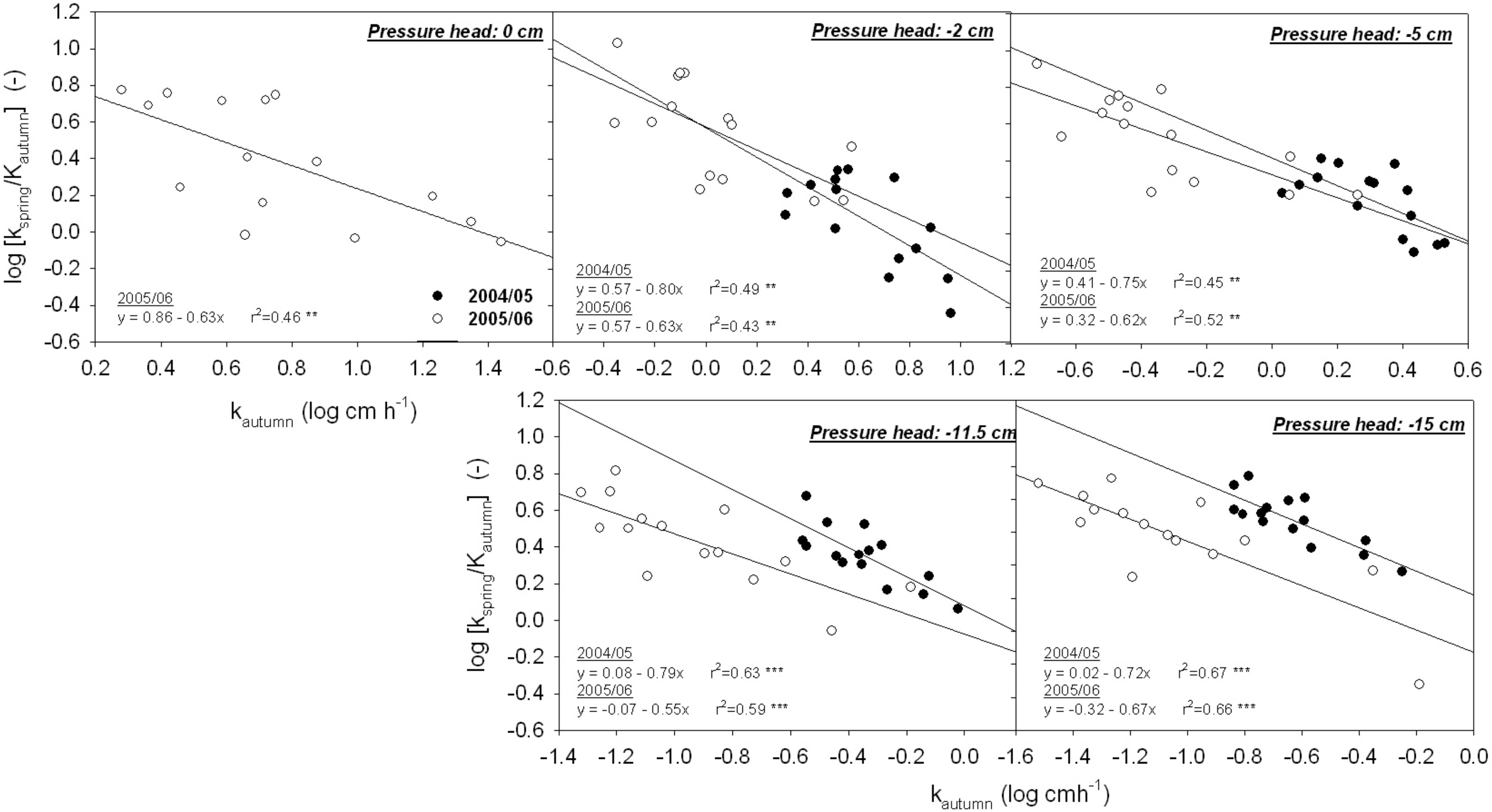
Average soil temperature (cf. Fig. 7.1) showed soil freezing to 10 cm depth for 70 days in 2004/05, with the main period of continuous frost between 17 January and 16 March and a minimum soil temperature of -1.37 °C. In 2005/06 soil freezing to 10 cm was measured during 88 days with permanent temperatures below 0° C between 13 January and 17 March and the lowest temperature measured being -2.40°C. From 25 January to 19 March 2006 sub-zero temperatures were also measured at 20 cm depth, while in 2004/05 we did not measure soil freezing below 10 cm. These observations are consistent with a higher frost induced conductivity increase of 65 % over winter in 2005/06, compared to 43 % in 2004/05.

MacIntosh and Sharratt (2003) described a greater reduction of the larger macropores over winter, having less stability than smaller pores. The change of hydraulic conductivity between autumn and spring in our study is consistent with this observation. Linear regression between the autumn conductivity and over-winter conductivity change showed that higher values of K_h in autumn will have less increase or even a decrease between the two measurement dates over all pressure heads (Fig. 7.7).

Based on this result, we performed analysis of variance for the influence of soil cover and topographical position on the change of hydraulic conductivity over winter using $K_{h,autumn}$ as a continuous covariate. In 2005/06 the bare soil treatment had the lowest increase in hydraulic conductivity over winter, with +25 %, +85 % and +92 % at 0, -2 and -5 cm pressure head respectively, being significantly less than the cover crops. Only the difference from mustard values was not significant at -2 and -5 cm. Also, for the first year the changes in the bare soil treatment were below those for the cover crops, being -24 % and + 26 % for -2 and -5 cm pressure head respectively. However the bares soil versus cover crop differences were not significant statistically. Thus, besides a general negative relation between the increase over winter and the size of hydraulic conductivity in autumn, expressed in a significant covariate in the analysis of variance, an additional significant soil cover effect was found, indicating that the bare soil treatment probably had a higher proportion of less stable macropores nearest to saturation in autumn.

Concerning topographical differences, we found a clear pressure head-specific effect on hydraulic conductivity. In both years a higher conductivity was observed at the toeslope near saturation, while at lower pressure heads it tended to be higher at the summit. The change in conductivity between autumn and spring relative to slope position shows a tendency to a greater increase of the conductivity at the toeslope. The increase in hydraulic conductivity at the summit was about 28 % less over the whole pressure head range in both years compared to the toeslope. However, this general trend was not significant statistically for all single pressure head sequences.

Figure 7.7 Linear regression between hydraulic conductivity before winter and the conductivity change over winter for 2004/05 and 2005/06.

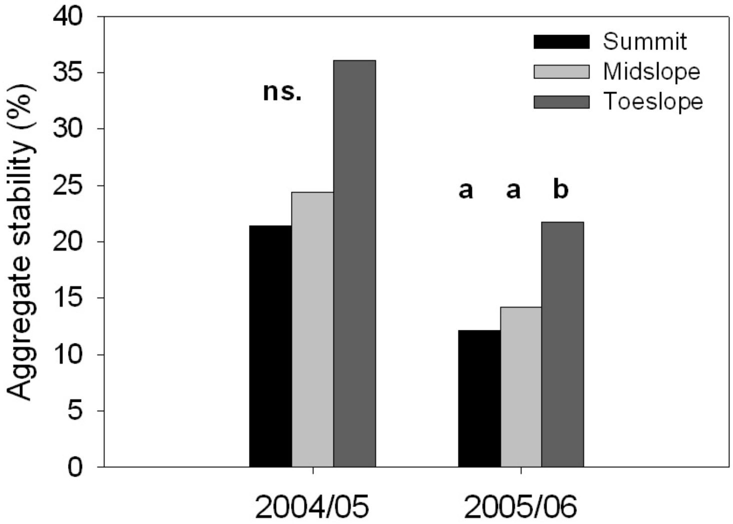


7.4.3 Sorptivity number

Sorptive number showed a particularly strong topographic effect along the slope. In both years the toeslope had the highest values over all pressure head ranges.

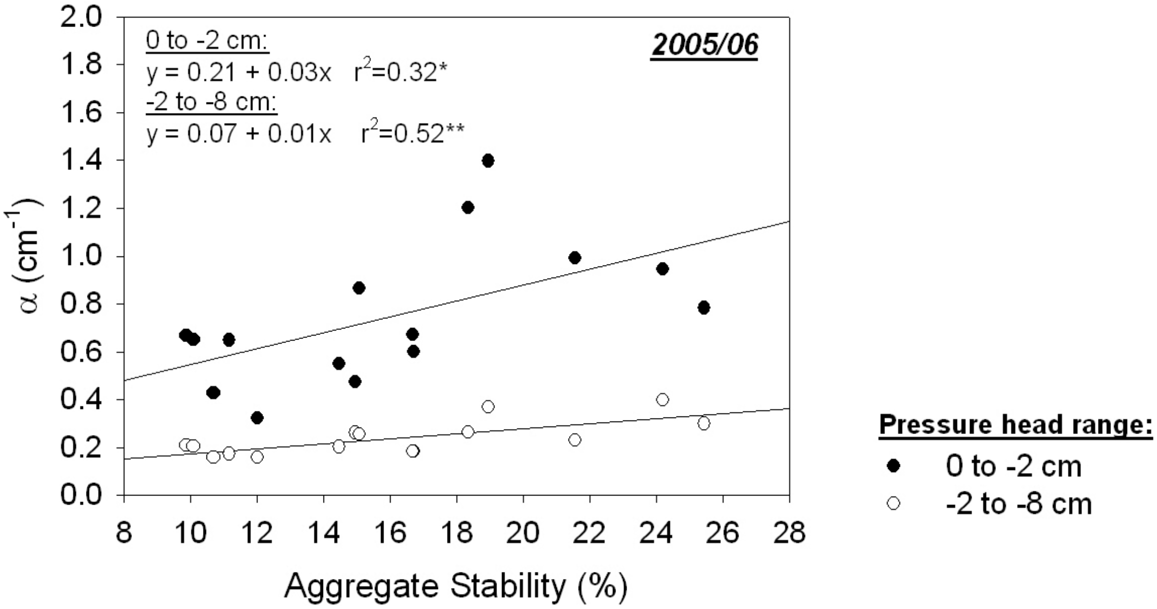
Fig. 7.8 shows the aggregate stability for both years in relation to slope position. (Differences between the cover treatments were not significant in both years.) As expected, there is a trend towards higher aggregate stability from the summit towards the toeslope, which was significant in 2005/06.

Figure 7.8 Average percentage of water stable aggregates (1-2 mm diameter) along the slope. *(Bars with the same letter are not different statistically at $p < 0.05$.)*



For 2005/06 we also found a significant linear regression between aggregate stability and sorptive number at the pressure head ranges of 0 to -2 cm and -2 to -8 cm (Fig. 7.9). A similar trend for the range of -2 to -8 cm observed in 2004/05 however did not result in a significant regression relation.

Figure 7.9 Linear regression between aggregate stability and sorptive number for the year 2005/06 at 0 to -2 cm and -2 to -8 cm pressure head.



As shown above (Fig. 7.5), in 2004/05 there was a significant decrease in sorptive number over winter for both pressure head ranges. In the second year the same tendency was found for the measurement range between 0 to -2 cm only. Plante and McGill (2002) studied aggregate dynamics using a tracer and showed a fast turnover rate of large macroaggregates, being less stable than smaller aggregate classes. Assuming that large inter-macroaggregate pores mainly affect sorptive number next to saturation, as suggested by the relation shown in Fig. 7.9, a decreasing slope of the alpha parameter over winter is likely to be related to the breakdown of macroaggregates and a shift towards pores between smaller particle size classes with a consequent increase in the relative importance of capillary to gravity driven water flux.

7.4.4 Pore radius, pore number and effective macroporosity

Flow weighted mean pore radius and the number of pores per square meter were derived from the infiltration measurements in the respective pressure head ranges on the hydraulic conductivity curve. To calculate effective macroporosity from infiltration measurements, different estimates of pore radius have been proposed (Bodhinayake et al., 2004).

Reynolds et al. (1995) discussed the difference between a flow weighted and a capillary-rise based approach to pore radius. Our results agree with their observations of only small increase in the flow weighted mean pore radius over a wide pressure head range. For 2005/06, including the range between 0 and -2 cm, only near to saturation did the λ_m pore radii have a higher increase. Within the pressure head range studied in our analysis, the flow weighted pore radius tended to approach the capillary-rise based estimates towards the lower end, while differences increase towards saturation. Reynolds et al. (1995) interpreted this phenomenon as being related to higher discontinuities for larger pores sizes and thus a higher effective contribution of smaller pores in the flow process as expected from capillary theory.

In the first year there was a trend towards a general decrease in pore radius over winter, while in the second year, only the pores in the pressure head range closest to saturation decreased. The bare soil treatment had the highest decrease in pore radius between the two measurement dates close to saturation, i.e. for 0 and -2 cm, and -2 to -5 cm pressure head. However analysis of variance of the relative change in flow weighted mean pore radius did not show significant differences between the soil cover treatments. Using the pore radius in autumn as a covariate, statistical analysis gave a significant influence of the covariate over the entire pressure head range. As discussed above, this reveals that the proportion of the porosity composed of very large pores shows less increase over winter or even decreases due to pore collapse. In this general trend, the direct influence of soil cover or topographical position was subordinated.

Considering Poiseulle's law, a shift towards smaller pore radii requires a significant increase in pore number to maintain a given water flux. As water conducting pores tended towards smaller pore radii in spring for the range next to saturation in 2005/06 respectively over the whole measured range of near saturated hydraulic conductivity in 2004/05, the observed increase in conductivity requires a substantially higher pore number. This resulted in an overall increase in effective macroporosity towards spring by 44 % in 2004/05 and 48 % in 2005/06. As described by Chamberlain et al. (1990), not only a reduction in large macropores, but even a decrease of void ratio over winter can nevertheless coincide with enhanced soil permeability due to increased micro-fissuring during freezing and thawing.

Effective porosity estimates based on infiltration measurement and a capillary-rise based constant pore radius result in a lower pore volume due to the larger mean pore radius assumed to transmit the water flow. For a silt loam soil, Dunn and Phillips (1991) reported a water conducting macroporosity between 0.021 to 0.077 % soil volume for an infiltration measurement range of -0.6 to -14 cm pressure head. Cameira et al (2003) found an effective porosity from infiltration measurements between 0 and -15 cm from about 0.03 to 0.08 % on a silt loam using minimum instead of mean capillary-rise based pore estimates. Values given by Bodhinayake et al. (2004) for a measurement sequence between -0.6 to -22 cm for the Dunn and Phillips approach on a silty loam were 0.016 %. For our study we found an average water conducting porosity of 0.023 % for the capillary-rise based pore radius estimates according to Dunn and Phillips. This is within the range observed by other authors.

Comparing estimates of water-conducting macroporosity in relation to both temporal and spatial dynamics, for the capillary based approach a change in hydraulic conductivity is translated into a corresponding change in number of water-conducting pores and effective porosity. The flow based approach integrates both, a shift in mean pore size responsible for the flow as well a change in pore number. For a fixed value of hydraulic conductivity, a change in pore radius of 10 % will induce changes in pore number of 52.4 % and in water-conducting porosity of 23.5 %. In this sense, the slight decrease in hydraulic conductivity in the range between -2 and -5 cm pressure head in fallow and vetch during the winter 2004/05, would result in a decreasing effective macroporosity in this range of -56 % and -16 % respectively assuming a constant pore radius. However, when considering pore dynamics over winter that resulted in a significant reduction of the average pore size for water transmission, in spite of the reduced hydraulic conductivity, water–conducting porosity increased.

7.5 Conclusion

In a two year cover crop trial, infiltration measurements using a tension disc infiltrometer were made and different water transmission properties were derived to characterize the soil structural pore space. The influence of cover crops compared to bare soil, the spatial differences along the slope and the temporal changes over winter were analysed.

The soil structure related hydraulic properties manifested a high natural variability. The impact of agricultural management such as cover cropping has been less than other factors, including climatic effects and topographical soil heterogeneity. Our findings suggest a general increase of hydraulic conductivity due to structure forming processes like freezing/thawing over winter. Changes in flow weighted pore radius indicate that particularly large pores (e.g. shrinking cracks) which formed in late summer and autumn tend to be less stable and will shift towards a smaller average pore size towards spring. This is revealed by a decrease in hydraulic conductivity between pre-winter and spring. This reflects simultaneous processes of structure formation and degradation over winter. Larger changes for some water transmission properties were found for bare soil, particularly in the pressure head ranges next to saturation. This suggests that bare soil is particularly susceptible to the impact of structure forming climatic factors on the soil surface, while soil coverage moderates their effects.

The topographic influence on water infiltration showed a clear tendency towards gravity driven flow through larger pores towards the toeslope where a higher content of clay particles and a higher aggregate stability is found. For the hydraulic conductivity the topographical effect on the temporal change over winter showed a tendency towards higher increases at the toeslope where structural stability of the soil aggregates is higher.

There was an overall tendency towards an increasing water-conducting porosity between autumn and spring which was particularly high if a simultaneous decrease in pore size that occurred mainly close to saturation was considered in the calculation procedure.

Cover crops have multiple effects on soil structure and hydrology relevant for agricultural soil and water management. We showed that fast water infiltration through climatically induced surface marcopores could be particularly pronounced for bare soil. If the risk of surface runoff is reduced for a soil covered by plants, a retardation of the infiltration flux to deeper soil layers could eventually be beneficial, enhancing water storage and uptake by the plants from the upper soil layers as well as reducing solute losses through macropore or preferential flow passes towards the groundwater.

In order to highlight the potential of management options in relation to the natural variability, a sufficiently high resolution in measurements is required. Also potential long term effects related to the carbon cycle should be considered. Tension infiltrometry allows an efficient characterization of temporal and spatial dynamics of soil structure and related soil hydraulic properties and is a promising method to be used for further work towards a dynamic hydraulic property description for water balance modelling.

7.6 Literature

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8 A simulation study of the water dynamics in a cover cropped field compared to fallow during autumn and winter

Abstract

Based on data of a hydrological field measurement site, the influence of four cover crop species (phacelia, hairy vetch, rye and mustard) on the soil water dynamics in a semi-arid region compared to bare soil was investigated using the model HYDRUS 1D. The hydraulic property functions of the model were parameterized by different field and indirect methods and the model was calibrated for the water content time series. The different methods resulted in a substantial variability of the Mualem-Van Genuchten parameters. For the upper soil layers the field methods gave better results as they included influence of soil structure, while the water content in the deeper layers were best simulated based on the hydraulic properties calculated with the pedotransfer function HYPRES. Actual evapotranspiration calculated from the water balance of the measurement data were compared to the simulated values. During the first year with higher rainfall during the cover crop vegetation period measurements indicated higher evaporative losses for bare soil, while the second year with a prolonged drought in autumn resulted in a 10.2 % higher cumulative evapotranspiration for the cover crops. The model suggested higher water losses under the cover crops in both years between 1.3 % in 2004 and 12.1 % in 2005. The simulated values of the single cover crops deviated from the measurement results between 0.8 % (rye 2005) and 36 % (vetch 2005). Transpiration accounted between 17.2 % and 52.6 % of the total evaporative losses. Model analysis of a scenario with a virtual water intensive and deep rooting cover crop showed a maximum of 30 % higher evaporative losses for dry conditions in autumn in comparison to fallow. The resulting differences in profile water storage in autumn to a soil depth of 100 cm however decreased to 2.8 % until spring. In the upper soil layer, water content differences in spring were negligible for both years. This resulted in non significant differences in the yield measured for the subsequent cash crops (sugar beet, spring barley, maize) during both years. From our results we concluded for cover cropping under semi-arid conditions that (i) the potential deep profile depletion of cover crops is reduced due to the low atmospheric demand during full cover crop growth and (ii) that the depletion of the upper soil layers, where water availability is essential for cash crop germination and youth development, is equilibrated over winter. Finally deviations between the simulation results and measurement data were discussed and major sources of uncertainty were located in (i) the water content measurements by access tube sensors (ii) the lower boundary flux calculations and (iii) the data base for the field parameterization of the hydraulic property functions of the HYDRUS model.

8.1 Introduction

Cover cropping has become a widely used agro-environmental instrument for sustainable soil management. Recent prognoses of climate change in Europe expect major impacts in the Mediterranean area, particularly in relation to drought (IPCC, 2007). For central and northern Europe, Seibert et al. (2007) showed a trend towards an increase in extreme weather events, i.e. heavy storms and prolonged dry periods. Under this scenario, the prevention of soil erosion, structure degradation and further decline in organic carbon content has become a focus in environmental and soil protection strategies across the European Union (European Commission, 2002).

Several studies have demonstrated the substantial contribution of cover cropping to mitigate the above mentioned soil degradation processes (e.g. Meyer et al., 1999; Liu et al., 2005; Guangwai et al., 2006). Water limited environments in the arid and semi-arid regions of Europe nevertheless are considered not to be adapted to a wide spread introduction of permanent soil cover by living plants as their transpiration demand could induce water storage depletion affecting the yield of cash crops. Islam et al. (2006) recently confirmed this concern by a modelling study on the water balance of cover cropped soils showing up to 30 % higher water losses to the atmosphere for the green manure plants compared to fallow. Other studies, however, suggest several mechanisms that could mitigate these adverse effects by an improved water infiltration and increased water storage capacity induced by cover cropping (e.g. Colla et al., 2000; Joyce et al., 2002) During several years of soil water content monitoring in a cover cropped agro-ecosystem in the semiarid region of Eastern Austria by means of different measurement techniques, only small differences in the post-winter profile water storage were found between a cover cropped and bare soil (Bodner et al., 2001).

Such contradictory results are obviously related to the complex and diverse impacts of a living plant cover on the soil water dynamics. Some important mechanisms of these plant-soil-water interactions should be reviewed shortly in relation to the components of the water balance that is generally given by (Ehlers and Goss, 2003):

$$P + I - R - E - T - D = \int_L^0 \frac{d\theta}{dt} dz \qquad (8.1)$$

where P is precipitation (mm), I is irrigation (mm), R is surface runoff (mm), E is soil evaporation (mm), T is transpiration by plants (mm) and D is drainage (mm) below the lower system boundary. The term on the right side gives the change of volumetric soil water content over time and in a profile of depth L.

All variables in Eq. 8.1 can be influenced directly or indirectly by living plants. If including an additional term for intercepted rain or irrigation water evaporating from the plant surface, even a potential impact of plants on the input quantity of water at the soil surface entering the system can be expected.

As shown by Hartwig and Ammon (2002), a plant or mulch cover of the soil surface could reduce runoff losses up to 95 % compared to a bare soil. Thus cover crops are likely to increase the amount of rainfall or irrigation water infiltrating into the soil. Quantitatively this effect will depend on several natural and human induced factors such as soil texture and structure, length and slope of the field, rainfall intensity, surface roughness induced by tillage and the percent soil surface effectively covered by the crops (Wishmayer and Smith, 1978).

Carof et al. (2005) studied the changes in infiltration under cover crops related to direct influences of the plant cover and roots on structural porosity. However, a quantification of the complex interactions of roots, organic matter and soil organisms with the mineral soil particles and their effects on the dynamics of soil porosity and pore size distribution is not yet available.

The gaseous water losses to the atmosphere, either by evaporation through the soil surface or via root water uptake for transpiration, can be subjected to multiple influences by a crop cover. Soil evaporation is limited to the upper parts of the soil profile. Based on the Darcy-Buckingham law of water flow, the quantity of evaporation water and the advance of the drying front with depth and time depends on both, unsaturated hydraulic conductivity and the pressure head gradient as the driving force of capillary rise to the evaporation surface. As described by Steiner (1994), based on several studies of mulching effects on soil water conservation, a bare soil surface can dry out more quickly due to a higher amount of radiation energy falling on the surface. This, however, may lead to a lower cumulative water loss due to a faster transition from the energy limited phase of the process to the falling stage when water transport to the surface is less than the potential atmospheric demand. The main difference between bare soil evaporation and plant transpiration in terms of potential water losses is the higher soil volume available for plant water extraction due to root penetration into deeper soil layers. Thus, when soil evaporation from the dried out surface layer is already reduced, plant water uptake may still continue at a higher rate owing to the access of roots to readily available water resources. Generally water uptake is assumed to be proportional to the root density distribution of the crop (e.g. Feddes and Raats, 2004) and thus will be substantially reduced when water availability decreases in the upper layers where the main part of the root system is concentrated. However, several authors described mechanisms of water stress compensation. Low density regions of the root system in deeper soil layers can equilibrate the reduced water availability from the upper parts by increasing their uptake from these less depleted parts of the profile (Li et al., 2001).

Concerning the drainage term in Eq. 8.1, lysimeter studies showed a higher groundwater recharge under fallow compared to cover copped plots over winter. This phenomenon has been studied particularly in relation to nitrate leaching (Stenitzer and Hösch, 2005). Intense precipitation events as well as post winter snow melting may exceed the root zone water holding capacity, particularly in light and shallow soils, and result in a percolation of water below the maximum rooting depth of the subsequent cash crop. Thus a higher amount of soil water uptake by the cover crops may be compensated over winter by a reduced flux below the lower system boundary towards the groundwater.

Finally, the water storage term may be influenced by cover cropping on a longer time scale by high organic matter input that may increase the storage capacity of a soil (Joyce et al., 2002).

To understand the water flow processes in a system, hydrological and soil-plant-atmosphere models can be used. These models are based on physical and/or empirical equations that are considered to describe the main elements and processes of the considered system. In this way, the influence of changes in the system boundary conditions, e.g. a different proportion of transpiration from total potential evapotranspiration, on the individual processes can be studied and empirical observations of a system state variable can be explained from a sound physical background.

Numerous models are available that describe single parts of the ecosystem (e.g. hydrology) up to integrated soil-plant-atmosphere models covering all important processes in a system and the interactions between different sub-systems (e.g. hydrology, carbon and nitrogen cycle, plant growth). The selection of an adequate model depends primarily on the research question, i.e. which processes should be explained, whether the interactions between sub-systems should be studied or the model should be used for prognostic purposes rather than for studying of a certain process.

The objectives of the present study are (i) to calibrate the hydrological model HYDRUS 1D in order to simulate the observed soil water content dynamics, (ii) to compare the modelled evapotranspiration with the values resulting from the field observation based water balance calculation and (iii) to analyse the differences in soil water fluxes between a cover cropped and a bare soil and highlight the hydrological mechanisms that should be taken into account when assessing the potential risk and/or mechanisms of mitigation of cover crop induced soil water depletion. Based on our results we will discuss both, methodological problems and sources of uncertainty in field data acquisition and model parameterization, as well as potential implications of our preliminary results for a sustainable cover crop management in water limiting environments.

8.2 Material and methods

8.2.1 Hydrological field measurement site

During the first experimental year, continuous measurements of the soil water content were performed using capacitance sensors (Adcon CProbe) installed via access tubes. In 2005 a full hydrological field measurement site has been set up in one replication (Fig. 8.1). The design is based on the concept of the “virtual lysimeter” (Kastanek et al., 2002). Table 8.1 gives an overview of the sensor equipment and measurement principles.

Figure 8.1 Hydrological field measurement site.

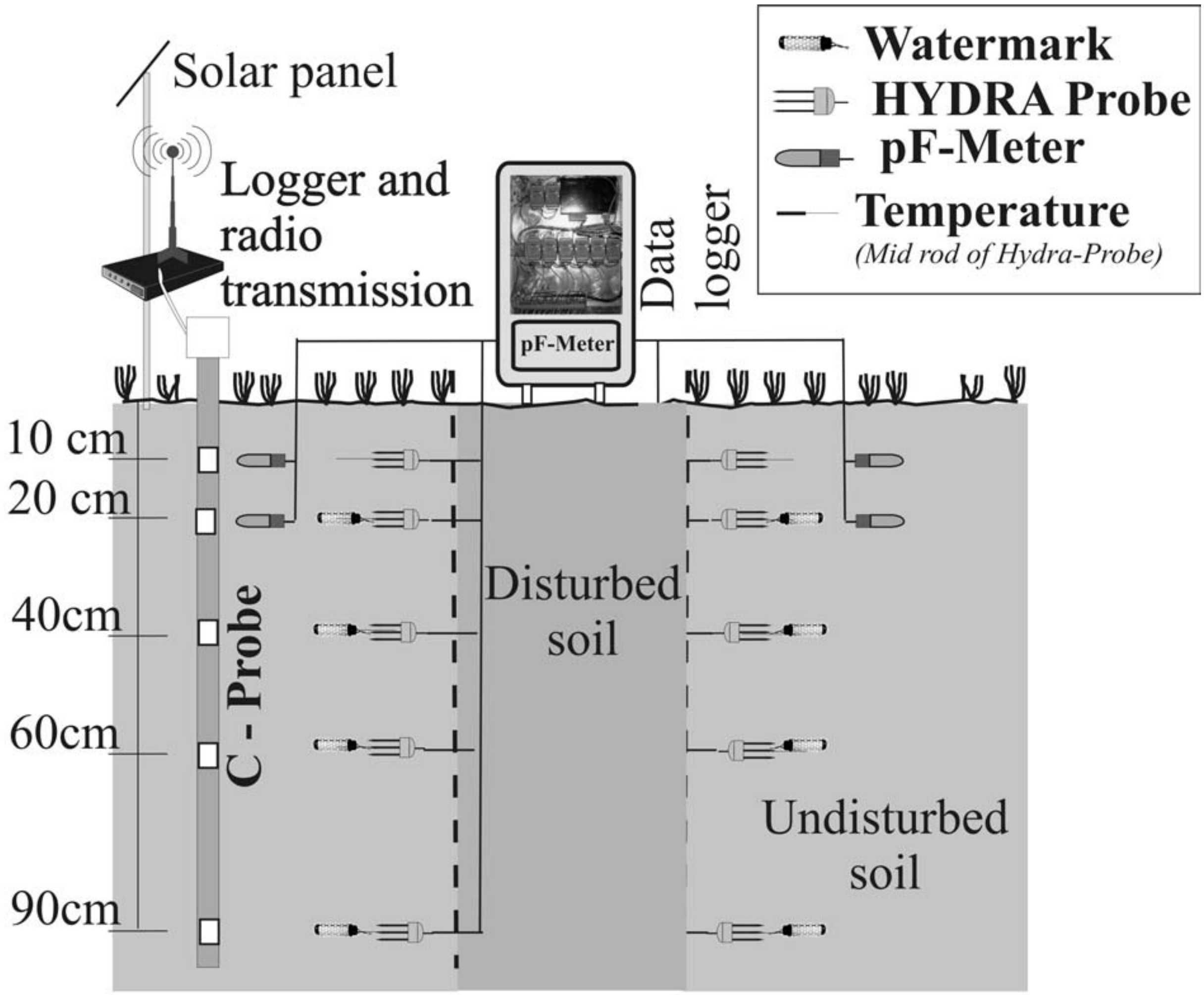


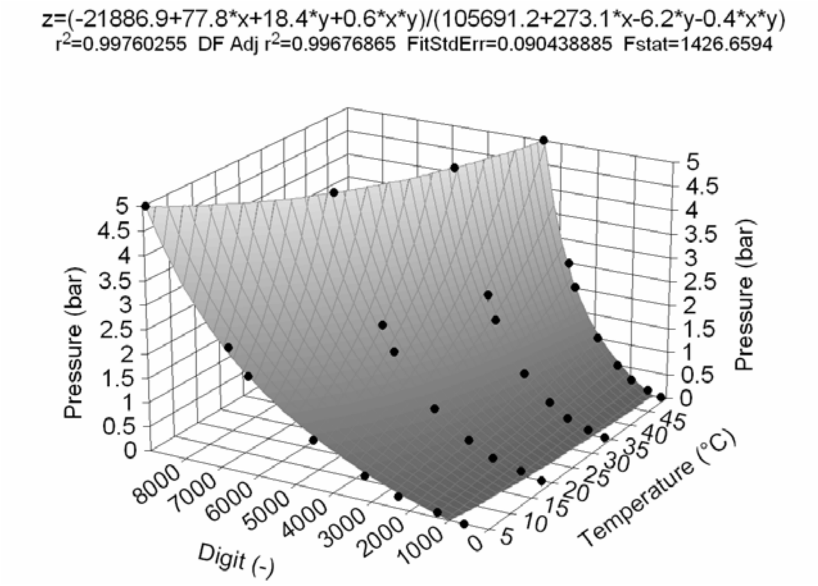
Table 8.1 Sensor equipment.

	Sensor *(Producer)*	**Measurement Principle**
Water Potential	Watermark *(Irrometer)*	Electrical resistance
	pF-Meter *(EcoTECH)*	Psychrometric
Water Content	C-Probe *(ADCON)*	Capacitance
	Hydra Probe *(VITEL)*[a]	Capacitance - FDR

[a]*Hydra Probe sensors are installed in the fallow and phacelia plot only.*

Watermark sensors have been calibrated prior to installation in the laboratory. Based on the calibration results, the electrical signal is converted to pressure head units and corrected for temperature based on a third order polynomial algorithm (Sokol, personal communication). The parameters of the calibration equation for each sensor were determined using Table Curve 3D. Figure 8.2 shows an example of the area fitting of the calibration equation to the measurement data obtained in the laboratory. The water content measurement devices have been run with the default calibration given by the producer. Hydra Probe sensors, being installed horizontally in the undisturbed soil of two plots, were used for comparison with the access tube devices that were available for all five treatments.

Figure 8.2 Watermark sensor calibration.



Water tension measurement in a semi-arid region is frequently facing the problem that water potential in the upper soil layer is lower than the measurement range of a tensiometer (~ -85 kPa). As an alternative, electrical resistance sensors like the Watermark granular matrix sensor with a measurement range up to -200 kPa can be used. However, one disadvantage of the resistance sensor, mainly in the upper layers object to fast changes in water content and water potential through precipitation and evapotranspiration, is slow response to these changes (Kastanek, 1996). Therefore a new sensor type based on a psychrometric principle was tested for the field measurement site. Parallel measurements of Watermark sensors and the psychrometric pF-meters in 20 cm soil depth are used for comparison of the measured data. Because of little experience with this new sensor type, the data were not yet used for further analysis.

The depth profile of the measurement devices has been determined based on the climatic and soil hydrological conditions as well as the main research questions. The high water holding capacity and low average precipitation at the experimental site results in only small fluctuations of the water content below 90 cm which has been observed for several years of previous experiments. As the research focus is the water dynamics in the main root zone of the cover crops and due to sensor limitations the deepest sensor was installed in 90 cm, while in the upper layers a smaller interval has been chosen.

All data for calculating the reference evapotranspiration by the Penman-Monteith method, i.e. air temperature, global radiation, relative humidity and wind speed, as well as precipitation are measured continuously at the experimental site by an automated weather station.

8.2.2 Water balance and calculation of actual evapotranspiration

The measurements from the hydrological field station were used to calculate the actual evapotranspiration by rearranging and simplifying Eq. 8.1 to:

$$E + T = P - D - \int_{L}^{0} \frac{d\theta}{dt} dz \qquad (8.2)$$

where the gaseous water losses to atmosphere (i.e. evaporation and transpiration) equal the amount of precipitation (irrigation is not used at the site and thus dropped from the equation) minus drainage losses below the lower system boundary by percolation minus the change in soil water storage over time, i.e. during the period of cover crop growth. Deep drainage below 90 cm soil depth was calculated following Darcy's law

$$D = -k_h \frac{\delta H}{\delta z} \tag{8.3}$$

where k_h is hydraulic conductivity (mm d^{-1}) and δH/δz is the measured hydraulic gradient at the lower boundary. As there were no measurements of hydraulic conductivity available for the deepest soil layer, the conductivity function was estimated with a pedotransfer function that was also used in model calibration.

The experimental field is also not equipped with a measurement site for surface runoff. However, in 2005 there were no erosive storm events exceeding an I_{30} of 12 mm h^{-1} during the measurement period relevant for the calculation of cover crop evapotranspiration. This threshold value is frequently used in erosion calculation (e.g. Wishmeier and Smith, 1978) and we therefore neglected the runoff term in the water balance.

In 2004 only water content was measured continuously. We therefore calculated monthly effective rainfall following the USDA procedure (USDA, 1970) to correct the input term for deep drainage and runoff in the water balance. This resulted in an estimate of the sum of drainage and runoff of only 1.1 mm in October and of 19.4 mm in November 2004. From 1st to 10th of December there was no rainfall. After the only intense rainfall of 37.8 mm on 9^{th} of November the measured increase in profile water storage was only 21.1 mm on average. Potential evapotranspiration was 0.26 mm for this day. This would result in water losses due to runoff and deep percolation of 16.4 mm for this storm event. Thus 85 % of the monthly runoff and deep percolation resulting form the effective rainfall calculation could be attributed to this single storm event. We therefore concluded that only for this day a correction is required for deep drainage and runoff in the daily water balance. For the other rainfall events, the assumption of no runoff and drainage will induce only insignificant error in the water balance. This is also supported by the water content measurements at 90 cm sensor depth showing no mayor changes during the cover crop vegetation period except after 9th of November.

8.2.3 Model description

The hydrological model HYDRUS 1D, Version 3.0 (Šimůnek et al., 2005) was used for analysing the soil water dynamics in the system that result in the observed time course of the measured state variable (i.e. water content) and the amount of soil evaporation and cover crop root water uptake.

The HYDRUS 1D model is a finite element model for simulating one dimensional movement of water, heat and solutes in variably saturated media. Saturated-unsaturated water flow is calculated by numerically solving the Richards' equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right] \text{-S} \tag{8.4}$$

where θ (cm cm^{-3}) is the volumetric water content, h (cm) is the matric potential, K (cm d^{-1}) is the hydraulic conductivity, z (cm) is the vertical axis directed upward, t (d) is time and S (d^{-1}) is the sink term. The closed form Van Genuchten equation (van Genuchten, 1980):

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha \mid h \mid)^n]^m} \tag{8.5}$$

and the Mualem equation (Mualem, 1976) to compute hydraulic conductivity

$$K = K_{sat}\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^l \left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{1/m}\right]^m\right\}^2 \tag{8.6}$$

are used to characterize the hydraulic properties. In Eq. 8.5 and 8.6, θ_s (cm cm^{-3}) is the saturated water content, θ_r (cm cm^{-3}) is the residual water content, K_{sat} (cm d^{-1}) is the saturated hydraulic conductivity, α (cm^{-1}), m (-), n (-) and l (-) are empirical shape parameters. The α parameter has been related to the air entry pressure h_b (cm) by Wagner et al. (2001) according to:

$$\alpha = \frac{1}{h_b} \quad (8.7).$$

The tortuosity parameter l is defined as the ratio of the average capillary tube length, L_e, to the length L of the porous medium (i.e. the soil sample) along the major flow axis (Moldrup et al., 2001):

$$l = \frac{L_e}{L} \quad (8.8).$$

Root water uptake is expressed by the sink term S in Eq. 8.4 representing the volume of water removed from a unit volume of soil per unit time. S is defined by (Feddes et al., 1978):

$$S(h) = \alpha(h) S_p(z) \quad (8.9)$$

where α(h) is a prescribed dimensionless stress response function ($0 \leq \alpha \leq 1$) and $S_p(z)$ (d^{-1}) is the potential water uptake rate at a certain depth.

When assuming a non-homogeneous root distribution, a general expression for S_p can be written as (Feddes and Raats, 2004):

$$S_p(z) = \frac{L_r(z)}{\int_{zr}^{0} L_r(z)dz} T_p \quad (8.10)$$

where $L_r(z)$ is the root density in a given soil depth and z_r is the maximum rooting depth (cm). Thus the potential root water extraction from a soil layer is proportional to the normalized root density present at the given depth and the potential transpiration T_p as an input parameter to the model. Root growth in HYDRUS 1D is modelled by a logistic Verhulst-Pearl equation.

For water stress response we used the S-shaped function proposed by van Genuchten (1987) and implemented in the model which is given by:

$$\alpha(h) = \frac{1}{1 + \left(\frac{h}{h_{50}}\right)^p} \quad (8.11)$$

where h_{50} (cm) represents the pressure head at which root water extraction is reduced by 50 % and p is a dimensionless shape parameter.

HYDRUS 1D also allows modelling water stress compensation following an approach presented by Jarvis (1989). The ratio of actual to potential transpiration is used as a water stress index ω and increased water uptake from deeper soil layers is calculated when ω reaches a user defined threshold value ω_c ($0 \leq \omega_c \leq 1$).

The parameter ω is calculated by:

$$\omega = \frac{\int_{zr} \alpha(h,x) b(x) dx}{T_p} \quad (8.12)$$

where b(x) is a normalized water uptake distribution function equal the first term at the right side of Eq. 8.10.

8.2.4 Parameterization of soil hydraulic properties and model calibration

Several methods for parameterizing the governing hydraulic property equations (Eq. 8.5 and 8.6) can be applied. Frequently laboratory measurements of retention data obtained from undisturbed soil samples in a pressure plate apparatus are used for fitting the van Genuchten model. As such data were not available, we used the following methods:

1. Field retentions curves: The van Genuchten function was fitted to data pairs of water content and matric potential from the hydrological measurement site using RETC (Van Genuchten et al., 1991)
2. Inverse parameter estimation from infiltration data: For the upper soil layer, tension disc infiltrometer data combined with volumetric water content measurements before and after the infiltration experiment were used for an inverse estimation procedure described by Šimůnek et al. (1998a) and implemented in the DISC software developed for this purpose by Šimůnek et al. (2000).
3. Pedotransfer functions (PTFs): Three pedotransfer functions were used to estimate the parameters of the hydraulic property models from measured particle size distribution, bulk density and organic matter content. The functions applied were two multiple regression equations by Wösten et al. (1999; HPYRES) and Rawls and Brakensiek (1989; RAWLS), and one neural network prediction by Schaap et al. (1998; ROSETTA) integrated in the HYDRUS software.

The soil profile was subdivided in five layers (0-10, 10-20, 20-40, 40-60, 60-90 cm) where data were available for the parameterization procedures.

The model predictions of soil water content with the hydraulic property functions resulting from the different parameterization methods were compared with the measured time series at the fallow plot for a calibration period of two month (29 September – 29 November). Differences between measured and modelled values were evaluated using root mean square error (RMSE), index of agreement and mean absolute percent error as statistical measures. Subsequently further calibration of the parameters to reduce RMSE was done starting from the values obtained with the method showing best agreement. The statistical parameters for model and measurement data comparison were calculated using the IRENE software (Fila et al., 2003). Following Moreels et al. (2003), the results of the statistical measures were ranked and the best parameter set was obtained by averaging the ranks over the five soil layers, as the target variable (soil water content) depends on fluxes across all layers.

As the position of the measurement devices was not the same in the two years and basic soil properties differed between the two locations, a separate parameter set for each year had to be determined to obtain a satisfactory description of the observed soil water dynamics.

The root water uptake parameters were derived from measured root length density data normalized according to Eq. 8.10 in order to represent the distribution of water extraction over the profile to the maximum rooting depth. Maximum rooting depth was taken at 60 cm based on the observations of the maximum depth of an upward hydraulic gradient from the pressure head measurements in the dry year 2005. For the Verhulst-Pearl root growth function it was assumed that 50 % of rooting depth is reached at half of the growing season.

8.2.5 Initial and boundary conditions

At the upper boundary a variable atmospheric boundary conditions was used, requiring daily data of precipitation, potential evaporation and potential transpiration. Potential evapotranspiration was calculated by the Penman-Monteith equation from measured weather data. The fraction of water losses to atmosphere by soil evaporation and plant transpiration respectively was obtained following an approach used in the SWAP model (van Dam, 2000):

$$T_p = ET_p - [(1\text{-}SC)\ ET_p] \qquad (8.13)$$

where T_p is the potential transpiration (mm), ET_p (mm) is the potential evapotranspiration calculated by the Penman-Monteith equation and SC (-) is percent canopy cover that was measured several times during the cover crop vegetation period.

A unit gradient free drainage condition was imposed at the lower boundary which is generally used to represent a situation where the groundwater table lies far beneath the model domain and therefore can be considered as adequate for the experimental site (Dixon, 1999).

The simulation period of water content was between 1 August and 1 April. Due to lacking information on the initial distribution of water content or pressure head over the soil profile, an initial condition was obtained by running the model with zero fluxes at the upper boundary until a stable distribution of pressure head was reached over the whole profile.

8.2.6 Model validation and scenario analysis

The main question in the modelling study was the quantification of the potential impact of cover crop root water uptake on water storage depletion and an analysis of changes in the water flow dynamics induced by the cover crops. The modelling results were evaluated in comparison with the observed water content time series and the cumulative evapotranspiration data obtained from the field measurement based water balance.

After validation of the water dynamics between December and March as well as water extraction of the cover crops, a “worst case” scenario analysis for the climatic and soil conditions at the site was performed with a “virtual” cover crop with high water requirements. For this virtual cover crop nearly complete soil cover, a crop coefficient of 1.1, a maximum rooting depth of 90 cm and full water stress compensation was assumed. A crop coefficient higher than one means, that the potential evapotranspiration of the crop exceeds the grass reference value. The value was taken from the tabulated crop coefficient of rapeseed (Allen et al., 1998) having a similar habitus as a mustard cover crop. The high soil coverage with a final value of 95 % results in a high proportion of evaporative losses attributed to plant transpiration via root water uptake. Profile water storage for this “water intensive” cover crop was compared to fallow at three stages, i.e. during cover crop growth, at the end of the cover crop vegetation period and in spring. Finally the differences of water balance components and flow dynamics resulting in the modelled system state were analysed.

8.3 Results

8.3.1 Soil water content measurements

Figure 8.3 shows the measured soil water content of the cover crops and fallow for the two experimental years from the beginning of the measurement until the probes had to be removed for seed bed preparation of the following main crop. Because the sensors were used with the default calibration, differences in the absolute water content should be interpreted with care as they can be related to a constant offset in the measurement signal. Also differences in soil texture at the single location of the probes can be a reason for a different water content reading. The higher values of vetch and rye in 2004/05 in the deeper soil layers are most likely related to a higher depth of the A_h horizon at the location of the sensors with a higher water storage capacity.

In 2004 changes of the response in soil water content to rain could be observed to a depth of 60 cm for all treatments during the cover crop growing period. Vetch and rye showed a slight increase at 90 cm soil depth after a mayor rainfall event on 9th of November and phacelia in late march with snow melting. In the dry year 2005 the water content time series reveal that rainfall infiltration during the measurement period did not exceed a depth of about 20 cm until spring. Some drastic changes in the upper soil layers towards low water content values observed during winter in both years are related to soil freezing and the respective change in the dielectric properties of the soil.

Figure 8.3 Soil water content (CProbe).

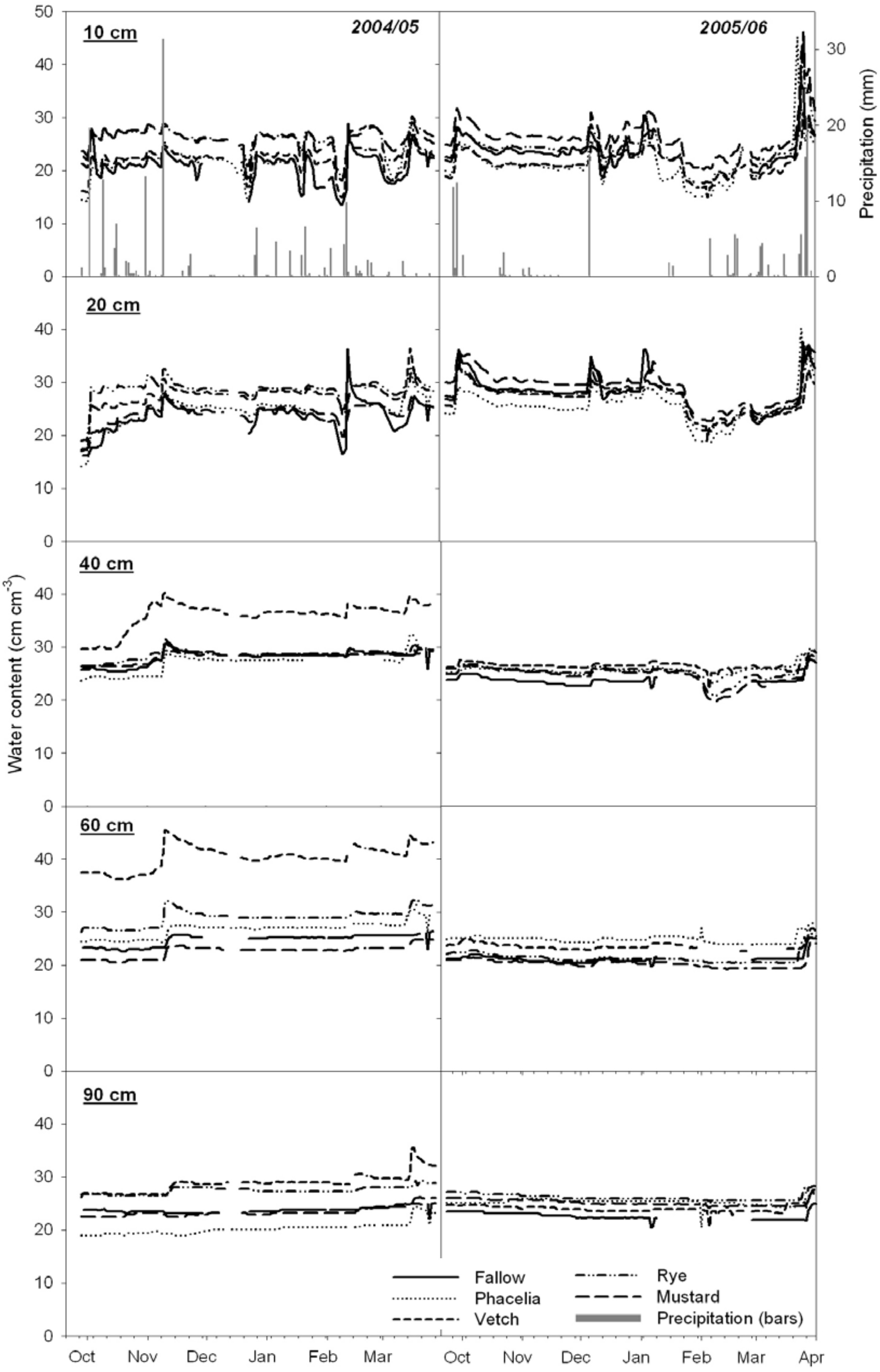
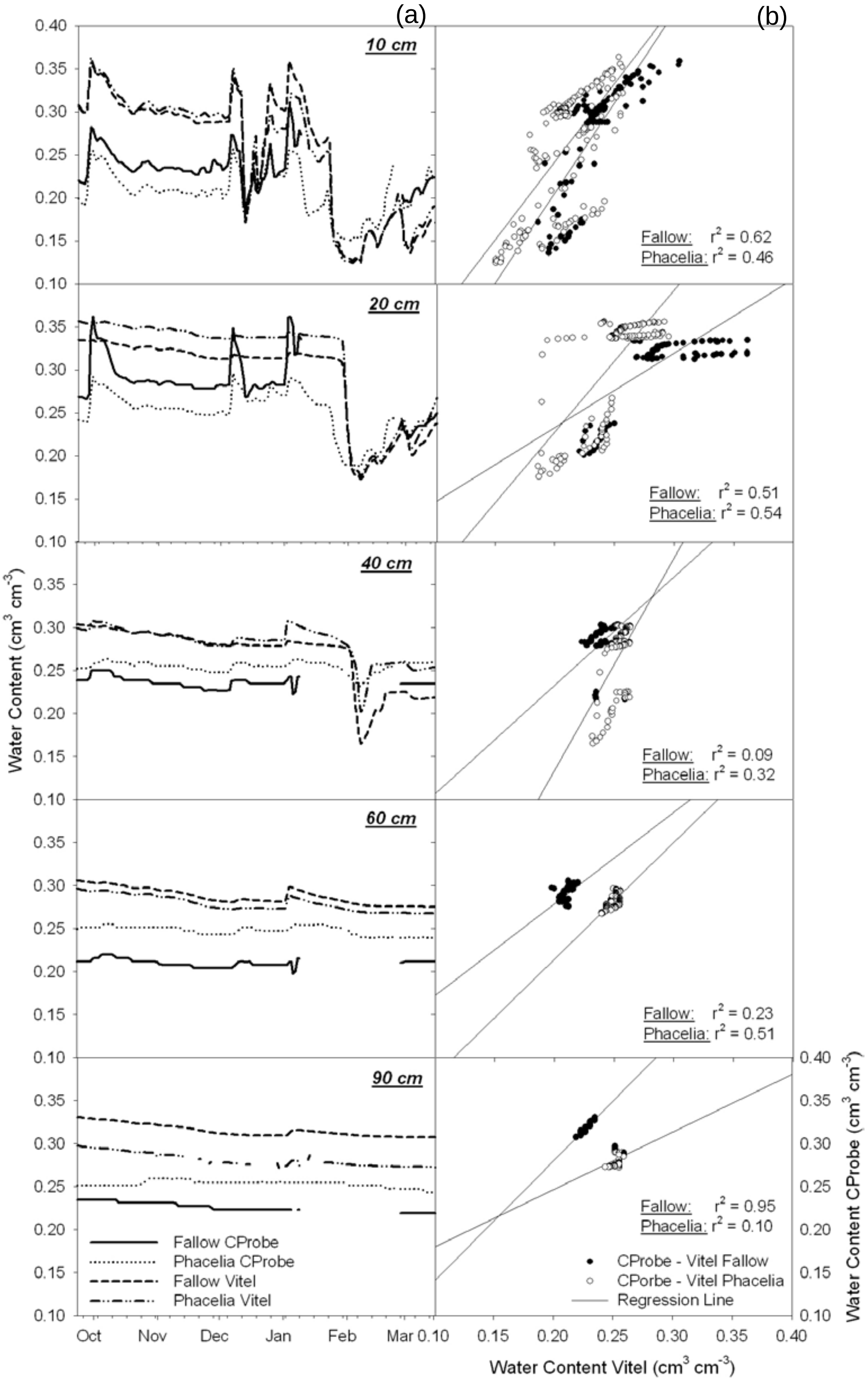


Figure 8.4 compares the water content measured by the CProbe sensor with the data from the Vitel Hydra Probe for fallow and phacelia where both sensors were installed.

Figure 8.4 Comparison of CProbe and Vitel Hydra Probe.



There is a clear offset between the two sensor types, but also differences in the measured water content changes between the probes are revealed (Fig 8.4a). Linear regressions between the two sensors' readings are all significant and show an r^2 between 0.09 and 0.95 (Fig 8.4b). Obviously significance is in some cases due to the high number of data pairs only. In the soil layers below 20 cm measurement depth, the data range is very tight leading to a poor regression coefficient. At 20 cm soil depth a substantial difference between the access tube probes and the horizontally installed Hydra Probes can be seen. While the Vitel sensors did not indicate any increase in water content after the higher rainfall events in mid September and mid December, the CProbe showed a high reaction in soil moisture at 20 cm. This is reflected in a poor correlation between the two sensor types at this depth.

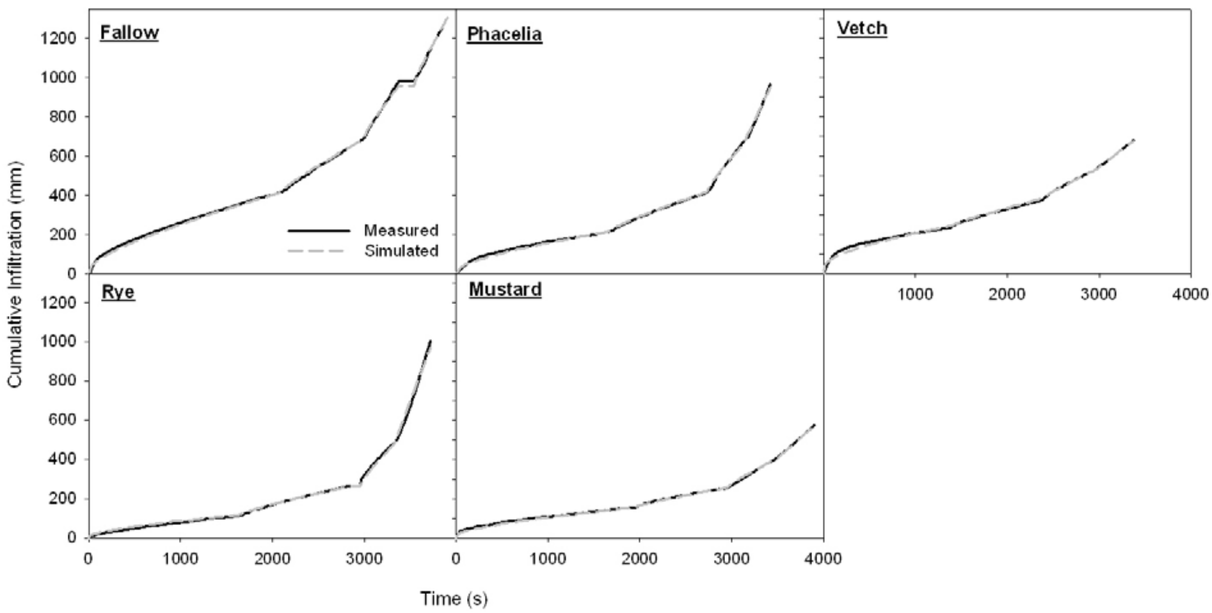
While the absolute differences between the sensors do not influence the values of actual evapotranspiration obtained from the water balance, as only relative changes will affect the result, the differences in the soil water dynamics, particularly the wetting of the soil in 20 cm suggested by the CProbe will have a substantial effect on the estimates.

8.3.2 Model Calibration

For studying the flow processes under the cover crops, HYDRUS 1D was calibrated. The fundamental soil water relations to be parameterized are the van Genuchten-Mualem retention and hydraulic conductivity functions. In 2004 only indirect parameter estimation using pedotransfer functions (PTF) based on particle size distribution and bulk density was possible. In 2005 two field methods were applied additionally, an inverse procedure for the first layer and field retention curves in the deeper layers.

Figure 8.5 shows the results of a tension disc infiltrometer experiment performed in spring 2006 for the inverse determination of the van Genuchten parameters.

Figure 8.5 Measured and modelled cumulative infiltration for inverse hydraulic property estimation using the DISC software.



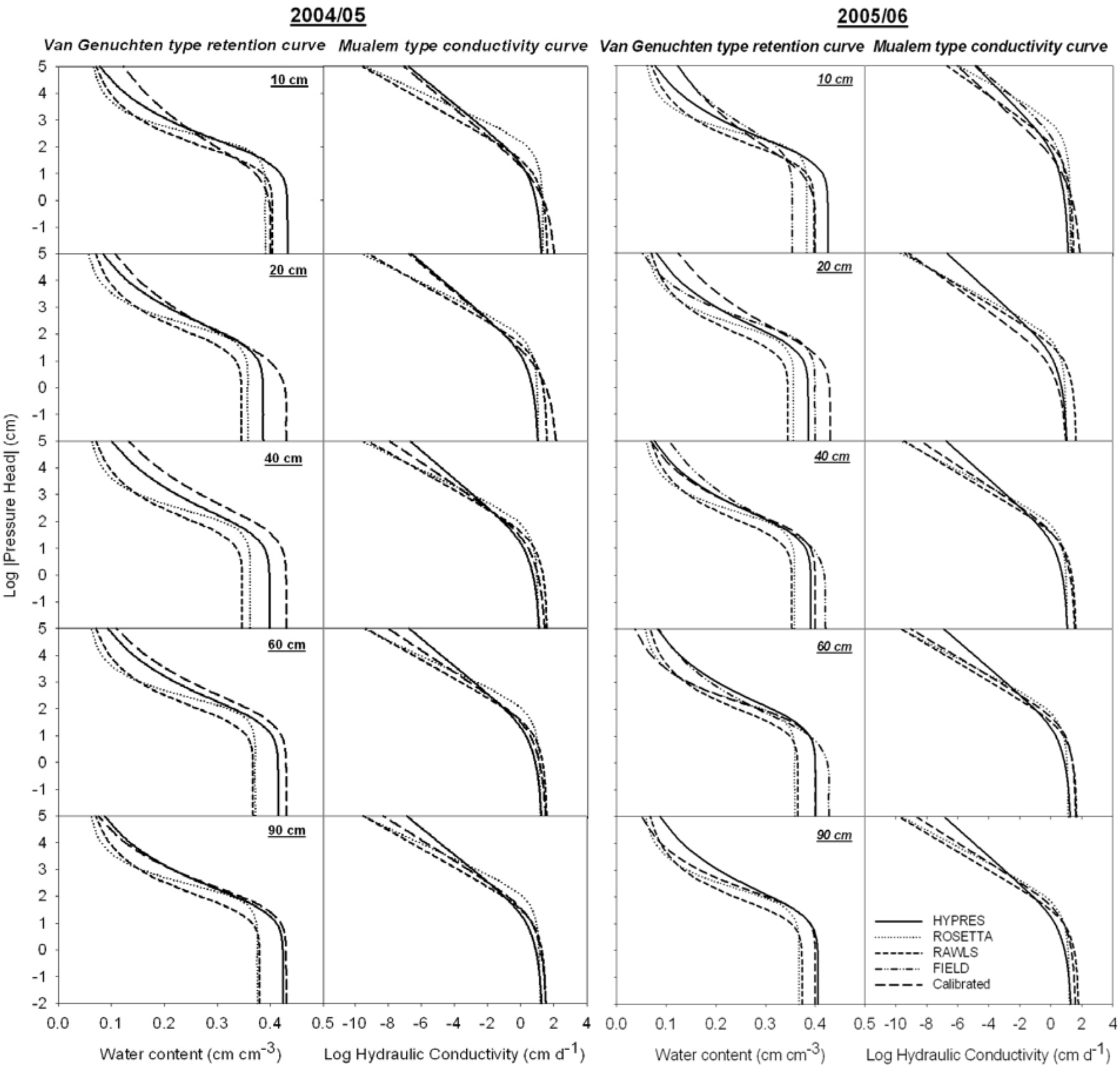
The measured cumulative infiltration was reproduced with high accuracy by the DISC-model. However, the spatial variability of the infiltration curves between the single treatments is high and thus the retention curve parameters will also vary significantly. The van Genuchten parameters generally showed a quite high value for α between 0.06 and 1.70 cm^{-1}. The range of the parameter n was between 1.075 and 1.406. A mean value was taken for the HYDRUS-parameterization. The averaged retention and conductivity curves resulting from the inverse method are shown in Figure 8.6 (10 cm, FIELD).

The data pairs of water content and matric potential from the hydrological measurement site allowed fitting a retention curve for 20, 40 and 60 cm. At 90 cm we did not apply this procedure as there was practically no variability of water content and matric potential at this soil depth during the measurement period and thus not sufficient data for a unique curve fit.

Therefore the HYPRES parameters where used at this depth. The resulting retention and conductivity functions are shown in Figure 8.6 (20 to 60 cm, FIELD).

In both years different pedotransfer functions were applied based on the measured particle size distribution, bulk density and, for the HYPRES PTF, also organic matter content. The resulting hydraulic property functions are shown in Figure 8.6.

Figure 8.6 Van Genuchten type rentention curves and Mualem type hydraulic conductivity curves.



The applied parameterization procedures resulted in substantial differences in the hydraulic functions, not only between PTF-based estimates and the field methods, but also within the PTFs. The neural network based ROSETTA and the multiple regression based Rawls and Brakensiek functions suggested a low saturation water content and a high n parameter, while HYPRES and the field methods showed a higher saturation water content and a lower n. In the upper layers (10 and 20 cm) the field data based procedures rendered a substantially higher *α* compared to the particle size based PTFs.

Figure 8.7 shows the measured and modelled water content for the two months used as calibration period applying the hydraulic property functions derived from the different methods described above. In order to improve the agreement between the measured and modelled results, additional calibration was done by varying the function parameters in the range of the different parameterization methods. The resulting calibrated hydraulic property models are shown in Fig. 8.6 (calibrated). Tables 8.2 and 8.3 show the statistical measures describing the model fit for the calibration period.

Figure 8.7 Comparison of water content measurements with values from simulation using different retention and conductivity curves resulting from different parameterization methods.

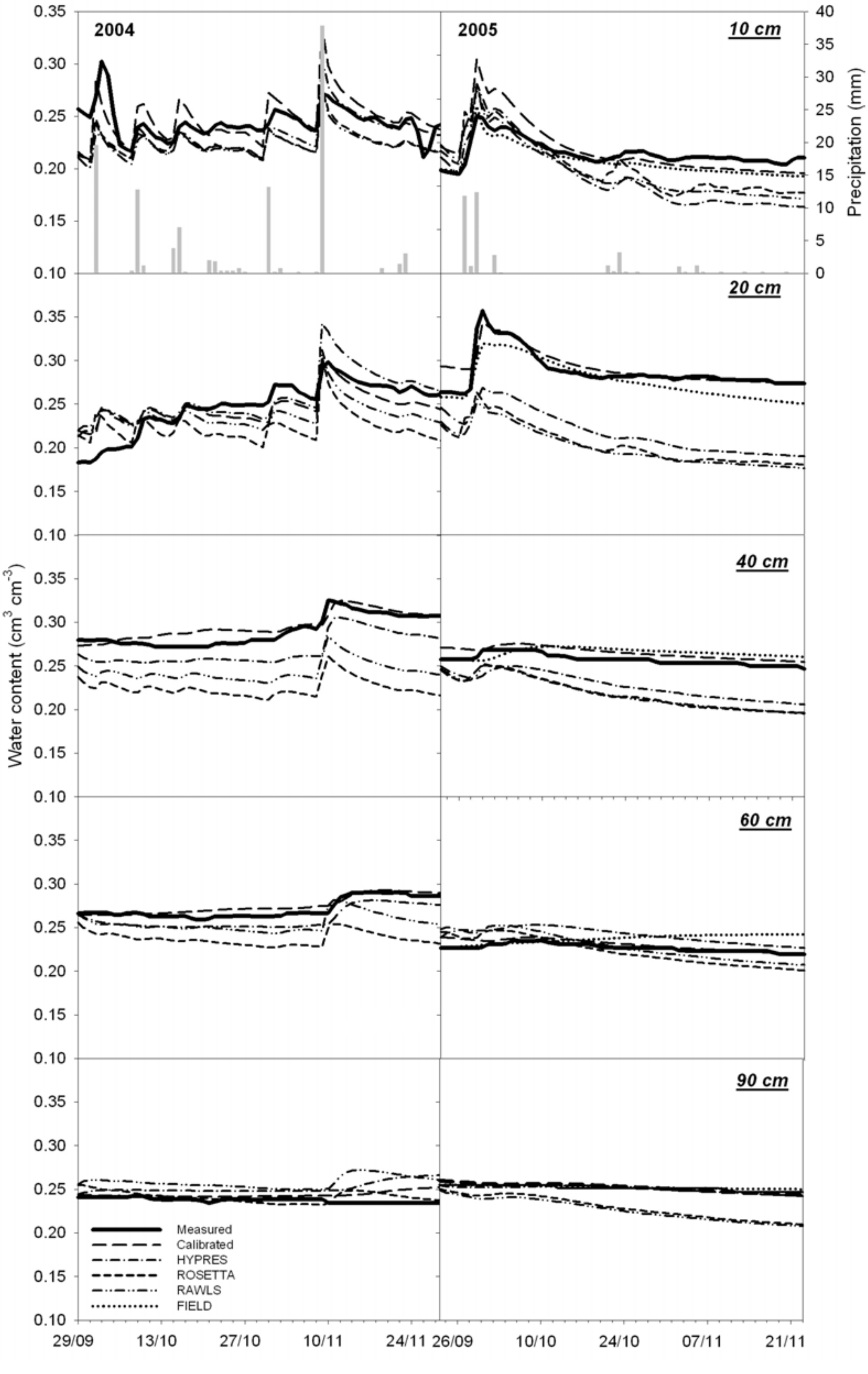


Table 8.2 Statistical measures of modelling agreement for 2004/05.

2004/05		HYPRES Value	Rank	ROSETTA Value	Rank	RAWLS Value	Rank	CALIBRATED Value	Rank
10 cm	RMSE[a] (cm^3cm^{-3})	0.037	4	0.021	3	0.020	2	0.019	1
	d[b] (-)	0.47	4	0.67	3	0.69	2	0.70	1
	ME[c] %	10.9	4	6.0	3	5.3	2	5.3	1
			Ø 4.0		*Ø 3.0*		*Ø 2.0*		*Ø 1.0*
20 cm	RMSE (cm^3cm^{-3})	0.020	2	0.037	4	0.027	3	0.019	1
	d (-)	0.86	1	0.54	4	0.64	3	0.82	2
	ME %	6.9	2	13.6	4	10.0	3	6.7	1
			Ø 1.7		*Ø 4.0*		*Ø 3.0*		*Ø 1.3*
40 cm	RMSE (cm^3cm^{-3})	0.022	2	0.067	4	0.048	3	0.007	1
	d (-)	0.71	2	0.32	4	0.41	3	0.91	1
	ME %	7.4	2	22.3	4	15.8	3	2.8	1
			Ø 2.0		*Ø 4.0*		*Ø 3.0*		*Ø 1.0*
60 cm	RMSE (cm^3cm^{-3})	0.012	2	0.036	4	0.018	3	0.006	1
	d (-)	0.78	2	0.36	4	0.58	3	0.93	1
	ME %	4.2	2	12.5	4	6.1	3	1.7	1
			Ø 2.0		*Ø 4.0*		*Ø 3.0*		*Ø 1.0*
90 cm	RMSE (cm^3cm^{-3})	0.016	4	0.007	1	0.022	3	0.008	2
	d (-)	0.15	3	0.41	1	0.15	4	0.25	2
	ME %	6.0	3	2.6	1	8.7	4	2.7	2
			Ø 3.3		Ø 1.0		Ø 3.7		Ø 2.0
Total mean rank			***2.6***		***3.2***		***2.9***		***1.3***

[a]*RMSE: Root mean squared error calculated as* $\sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}$ *where E_i is the ithmodelled value, M_i is the ith measured value, and i…n is the number of values.*

[b]*d: Index of agreement (0-1) calculated as* $1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|E_i - \overline{M}\right| + \left|Mi - \overline{M}\right|\right)^2}$ *where $\overline{M}$ is the arithmetic mean of the measured values.*

[c]*ME: Mean absolute percent error calculated as* $100 \cdot \sum_{i=1}^{n} \frac{|E_i - M_i|}{|M_i|} \cdot \frac{1}{n}$

Table 8.3 Statistical measures of modelling agreement for 2005/06.

2005/06		HYPRES		ROSETTA		RAWLS		FIELD		CALIBRATED	
		Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank
10 cm	RMSE[a] (cm^3cm^{-3})	0.037	5	0.027	3	0.030	4	0.012	1	0.020	2
	d[b] (-)	0.57	5	0.66	3	0.60	4	0.86	1	0.80	2
	ME[c] %	13.8	5	10.2	3	11.7	4	4.4	1	6.5	2
			Ø 5.0		*Ø 3.0*		*Ø 4.0*		*Ø 1*		*Ø 2.0*
20 cm	RMSE (cm^3cm^{-3})	0.004	3	0.005	4	0.005	5	0.001	2	0.001	1
	d (-)	0.32	3	0.27	4	0.26	5	0.87	2	0.92	1
		24.2	3	29.1	4	30.2	5	4.4	2	2.3	1
			Ø 3.0		*Ø 4.0*		*Ø 5.0*		*Ø 2*		*Ø 1.0*
40 cm	RMSE (cm^3cm^{-3})	0.002	3	0.002	4.5	0.002	4.5	0.001	2	0.001	1
	d (-)	0.31	3	0.24	4	0.24	5	0.43	2	0.70	1
	ME %	11.5	3	15.1	4	15.1	5	3.7	2	3.0	1
			Ø 3.0		*Ø 4.2*		*Ø 4.8*		*Ø 2*		*Ø 1.0*
60 cm	RMSE (cm^3cm^{-3})	0.001	5	0.001	3	0.001	3	0.001	3	0.0002	1
	d (-)	0.42	4	0.59	3	0.61	2	0.21	5	0.81	1
	ME %	6.3	5	5.1	4	4.6	2	4.7	3	1.6	1
			Ø 4.7		*Ø 3.3*		*Ø 2.3*		*Ø 3.7*		*Ø 1.0*
90 cm	RMSE (cm^3cm^{-3})	0.003	2.5	0.024	4	0.027	5	0.002	1	0.003	2.5
	d (-)	0.84	2	0.22	4	0.20	5	0.83	3	0.88	1
	ME %	1.0	3	8.9	4	10.0	5	0.5	1	0.9	2
			Ø 2.5		*Ø 4.0*		*Ø 5.0*		*Ø 1.7*		*Ø 1.8*
Total mean rank			**3.6**		**3.7**		**4.2**		**2.1**		**1.4**

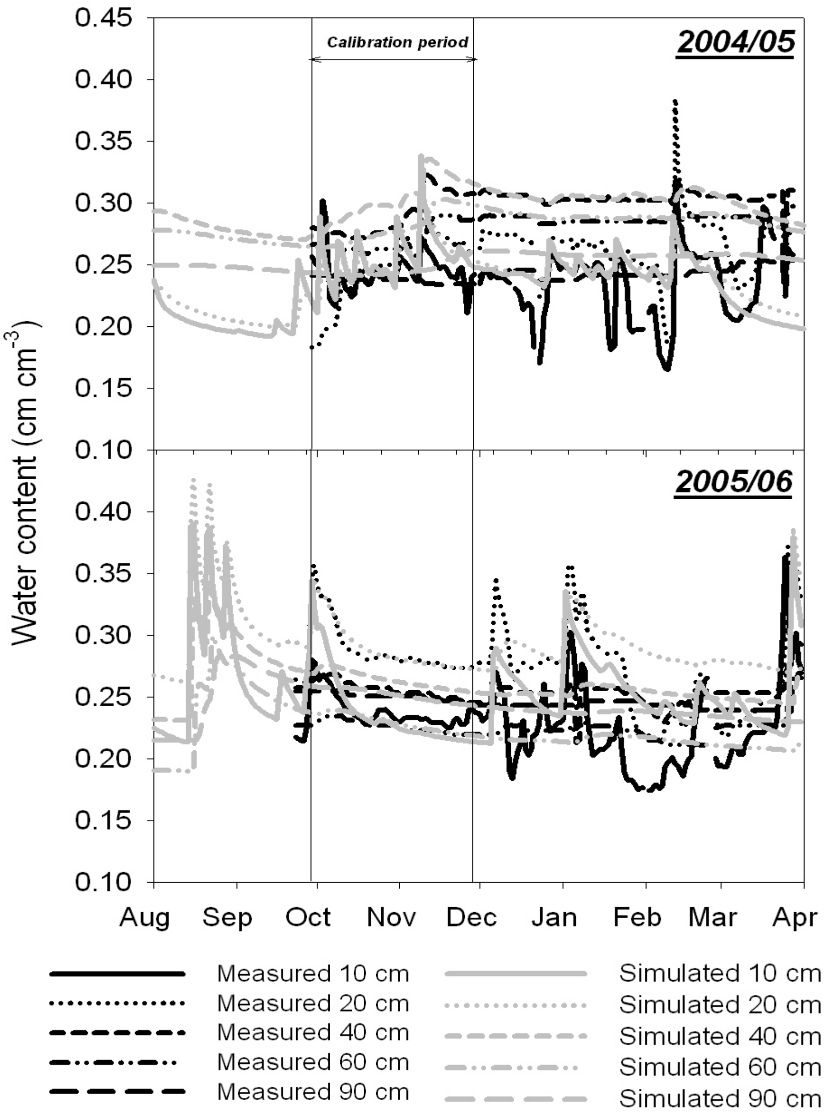
[a,b,c] *For explanation of the statistical measures see footnotes at Table 3*

As expected, the additional calibration improved the model fit and thus resulted in the best ranking compared to the other parameterization methods. The field data based parameterization applied in 2005 gave better results as the use of a PTF. For the further modelling steps, i.e. validating the simulation of the water content dynamics, comparing of simulated evapotranspiration values with the water balance based estimates as well as for scenario analysis, the calibrated hydraulic property functions were used for both experimental years.

8.3.3 Validating water content and evapotranspiration simulation

The simulation of soil water content was validated using the remaining measurement data after the calibration period until spring. Fig. 8.8 shows the modelled and measured soil water content time series for the bare soil treatment.

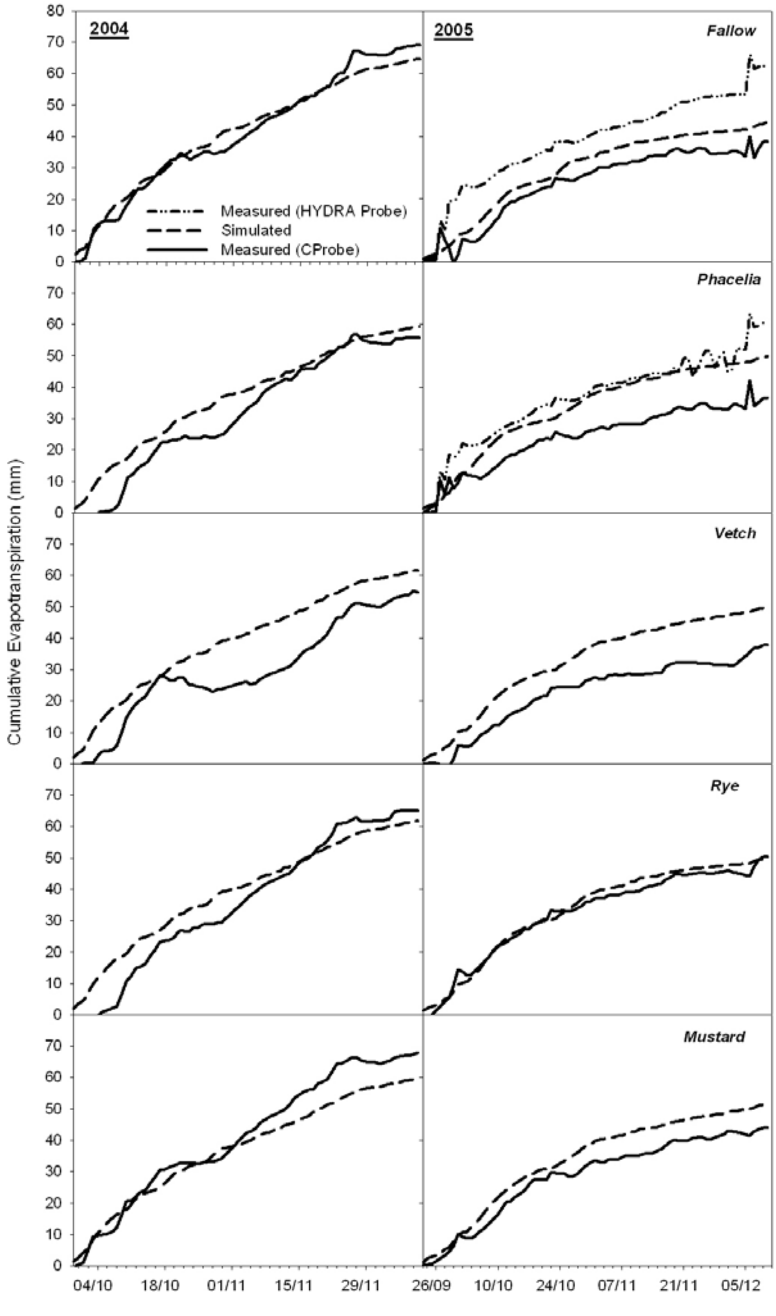
Figure 8.8 Simulated and measured soil water content for bare soil.



Measurements started at mid September. Based on the calibrated model, additional values from 1 August until beginning of the measurements were extrapolated. During winter, higher deviations between the modelled values and the measurements were observed particularly in the upper 20 cm that are probably related to soil freezing leading to an abrupt drop in the sensor signal. In 2004/05 the period of snow melting also led to higher errors in the modelled water contents. The high snow accumulation during winter in the first year and consequently a high amount of water infiltrating into the soil with snow melting was not represented by the model, even when using the snow hydrology option of the HYDRUS software. The RMSE for the validation period was highest in the upper layers (10 cm and 20 cm) ranging from 0.035 to 0.033 cm cm^{-3} in 2004 and 0.038 to 0.048 cm cm^{-3} in 2005 respectively. This corresponds to a mean percent error between 9.8 % and 10.9 % for 2004 and 12.3 % to 18.8 % for 2005. In the deeper layers the deviations were less, ranging from 0.010 to 0.015 cm cm^{-3} in 2004, and 0.010 to 0.016 cm cm^{-3} in 2005. The respective percent error was below 5 %, except for the 90 cm in 2004 (5.9 %).

The modelled actual evapotranspiration, i.e. the sum of root water uptake and soil evaporation for the cover crops and evaporation only for the fallow, cumulated over the measurement period between mid September until the end of the cover crop vegetation in December, are compared to the water balance based values in Figure 8.9. For fallow and phacelia, the results for both sensor types, CProbe and Hydra Probe, are shown.

Figure 8.9 Measured and modelled actual evapotranspiration.



In 2004 the differences between the cumulative measured and modelled evapotranspiration were between 5 and 13 %, in 2005 differences were larger, ranging form a very strong agreement for rye with a final difference of only 0.7 % to 36 % for vetch.

For those plots where both sensor types have been used, it can be seen that also the results from the water balance calculation show substantial differences depending on the measurement device.

In general, the values derived from the water balance in the dry year 2005 were lower than the modelled ones. In 2004 the modelled values were lower for mustard and rye and higher for vetch and phacelia. The water balance based estimates resulted in a mean difference between fallow and the cover crops of +6.3 mm (+10.1 %) in 2004. In 2005 fallow had lower evaporative losses than the cover crops by -3.8 mm (-9.2 %). The modelling results suggested lower evaporative losses for fallow in both years being -0.8 mm (-1.3 %) in 2004 and -5.9 mm (-12.1 %) in 2005.

Thus the general trend of low differences in evapotranspiration between a fallowed and a cover cropped field under conditions of regular rainfall – when the measurement based values even suggested higher water losses for fallow - and an increasing difference for dry conditions could be reproduced by the model.

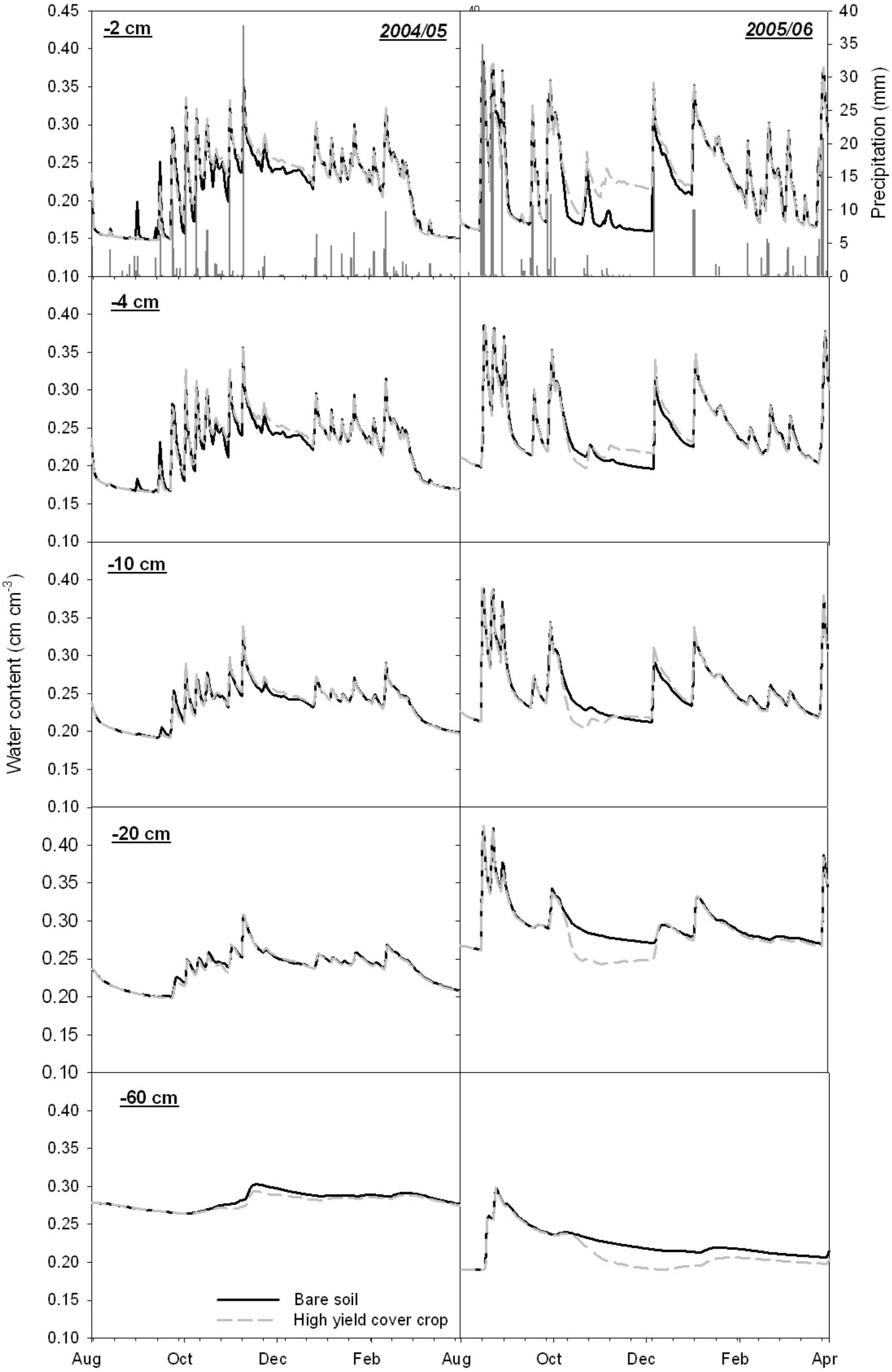
Also the range of the higher water losses for the cover crops in the dry year with around 10 % for the cover cropped treatments was described satisfactorily by the model. The differences between the single cover crop variants however could not always be represented accurately by the simulation.

8.3.4 Scenario analysis

Scenario analysis was performed for a bare soil compared to a virtual non-winter hard, deep rooting cover crop with fast soil coverage and a total final canopy cover of 95 %. Potential evapotranspiration was calculated by multiplying the Penman-Monteith reference evapotranspiration by a tabulated crop coefficient for rapeseed. Root water extraction was assumed proportional to a linearly decreasing root distribution function as proposed by Prasad (1988) and full water stress compensation was selected. The focus of the scenario analysis was to study the range of differences in the water balance components and analyse the underlying soil water dynamics, particularly in the soil layers close to the surface where most water fluxes occurred in 2005 and where direct measurement is difficult.

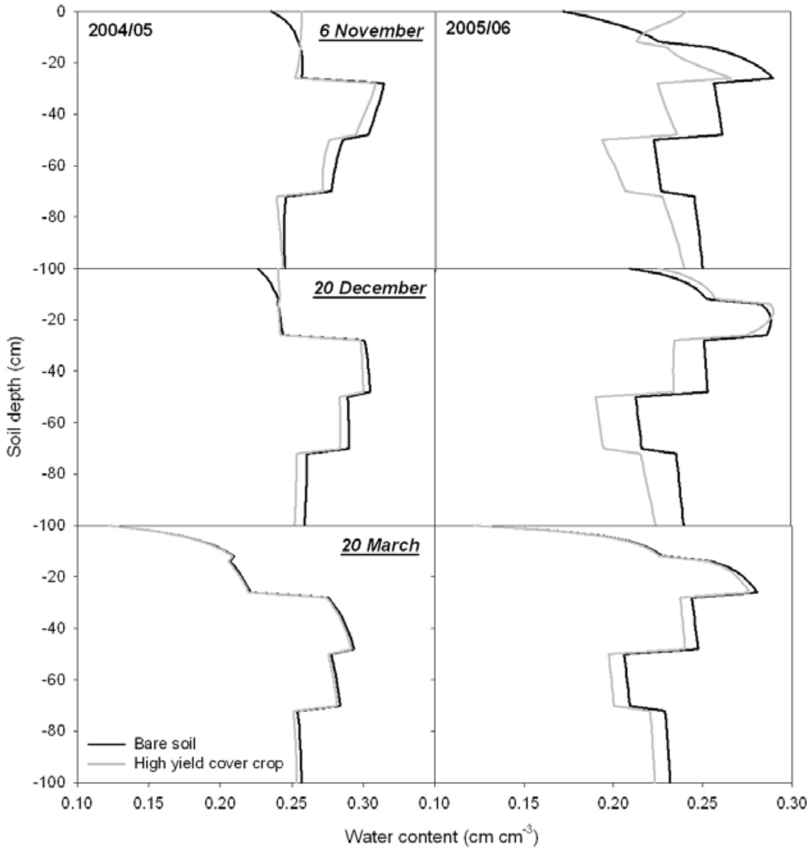
Figure 8.10 shows the modelled soil water content for bare soil and for the high yielding cover crop scenario at different soil depths with a high resolution in the upper parts of the soil profile. It can be seen that in the upper layers, down to 10 cm soil depth, soil water content is slightly higher for the cover cropped variant, particularly under the situation of lacking rainfall in autumn 2005. With increasing depth a lower water content due to the water extraction by the cover crop roots can be seen mainly under dry conditions when a root water uptake from deeper soil layers compensates the water shortage in the upper parts of the profile. The relation of actual to potential evaporation (E_{act}/E_{pot}) and actual to potential transpiration (T_{act}/T_{pot}) respectively can be used as an indicator of the water stress induced reduction of evaporative losses. In 2004 the values were 0.55 for bare soil, 0.67 for cover crop transpiration and 0.37 for evaporation under the cover crops. In 2005 bare soil had a mean E_{act}/E_{pot} of 0.64, for cover crop transpiration a value of 0.76 and for cover crop evaporation of 0.71 was found. The generally lower water stress induced reduction of transpiration compared to evaporation reflects the sustained profile depletion by root water uptake from deeper layers.

Figure 8.10 Model estimates of water content for fallow vs. a virtual high yielding cover crop.



Of particular interest for agriculture is the profile water storage after winter before seeding of a succeeding main crop. Figure 8.11 shows the profile water storage for the simulated scenario (a.) during cover crop growth (6 November), (b.) at the end of the cover crop growing season (20 December) and (c.) in spring (20 March) when cover crop residues are incorporated during seed bed preparation.

Figure 8.11 Model estimates of profile water content distribution for fallow vs. a virtual high yielding cover crop.



In 2004/05 the water storage differences to a profile depth of 100 cm were negligible in spring. During the dry vegetation period of 2005/06, soil moisture depletion under the cover crop exceeded the bare soil by 16.4 mm in November and decreased towards spring to 6.4 mm.

Table 8.4 shows the simulated water balance components for the two years for a simulation period between cover crop seeding and the end of March.

Table 8.4 Simulated water balance components[a].

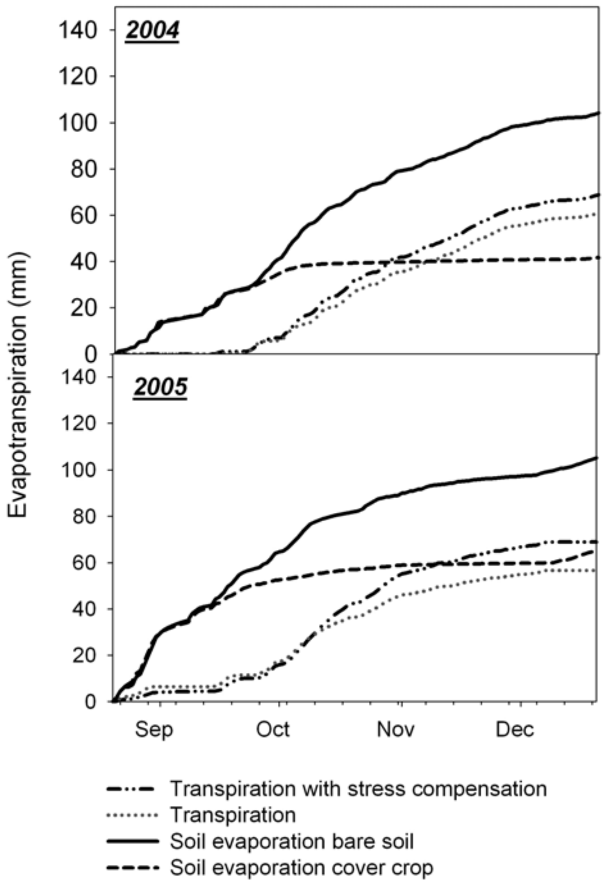
		E	T	P	D	R	ΔS
		mm					
2004/05	Bare Soil	-174.0	0	189.7	-9.8	0	5.9
	Cover Crop	-110.4	-69.5	189.7	-9.2	0	0.6
2005/06	Bare Soil	-166.9	0	200.7	-75.5	0	-41.7
	Cover Crop	-126.6	-68.9	200.7	-53.4	0	-48.2

[a]*cf. Eq.8. 1 for abbreviations*

In 2005/06 substantially higher fluxes through the lower system boundary occurred for both, the cover crop and bare soil scenario after the high precipitation in summer (152 mm in August) which are also related to a high relative saturation of the profile due to high precipitations in July (134 mm). Furthermore at the plots where measurements were performed in 2005/06, there was a slightly higher sand content at the deeper soil layers and thus the hydraulic property functions used for this year resulted in less storage capacity compared to the profile characteristics at the plots in 2004/05. Deep drainage losses under the root zone during winter and spring, however, were clearly reduced for the cover crop scenario compared to fallow as a higher amount of the infiltrating water was used to refill the water reservoir previously depleted by root water uptake. Plant water uptake in 2004/05 is largely a redistribution of evaporative losses towards transpiration. In 2005/06 the high reduction of surface evaporation by the prolonged drought and the sustained plant water extraction from deeper layers resulted in a slightly higher profile water depletion under the cover crop that however was reduced towards spring as shown above.

Figure 8.12 sums up the single components of water losses to the atmosphere during the vegetation period for the cover crop scenario compared to bare soil evaporation.

Figure 8.12 Cumulative evapotranspiration components of fallow vs. a virtual high yielding cover crop.



The cumulative water losses by soil evaporation from fallow are 104.2 mm in 2004 and 105.2 mm in 2005. Soil evaporation under the cover crop scenario is 41.7 mm in 2004 and 65.4 mm in 2005, while transpiration amounted to 60.9 mm in 2004 and 56.7 mm in 2005. The stress compensation increases the amount of transpiration water losses by 8.6 mm and 12.2 mm, respectively. Thus the sum of the evaporation and transpiration component accounts for 102.5 mm (110.5 with full stress compensation) in 2004 and 122.1 mm (134.3 mm) in 2005 being -1.6 % (+6 % higher) less in 2004 and +16.1 % (+27.6 %) higher in 2005 compared to fallow. Soil evaporation during the cover crop vegetation period accounted for 40.6 % (37.5 % with stress compensated root water uptake) of total water losses to the atmosphere for the cover crop treatment in 2004 and 53.5 % (48.7 %) in 2005.

The different amount of evaporative losses from the surface near layers under the two scenarios and the related differences in water content and pressure head distribution over the soil profile also have some effect on the infiltration fluxes. Figure 8.13 shows the water fluxes after a rainfall event of 16.2 mm in December 2005 after the prolonged dry period.

Figure 8.13 Profile characterization before rainfall (a) and water fluxes after a rainfall (b).

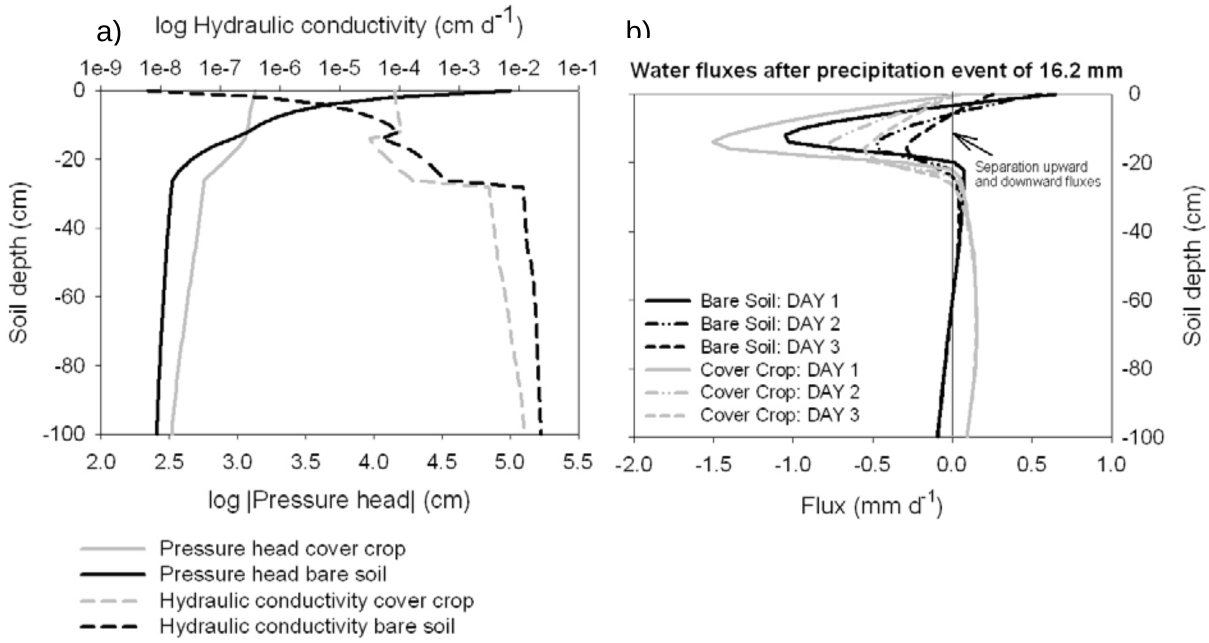


Figure 8.13a shows the pressure head and the hydraulic conductivity one day before the rainfall occurred. The lower pressure head near the soil surface under the bare soil is related with a substantially lower hydraulic conductivity. Until three days after the precipitation event, the infiltration front reached a depth of about 30 cm (Fig. 8.12b). For the cover crop a higher volume of water infiltrated to deeper soil layers, while the bare soil treatment showed higher upward fluxes, i.e. evaporative losses, immediately after the rainfall event. Thus in the highly depleted bare soil a higher amount of infiltration water was conserved in the upper centimetres, being readily evaporable. For the cover cropped soil a higher hydraulic conductivity in the upper layers resulted in higher volume of the rainfall water penetrating deeper into the profile to the root zone.

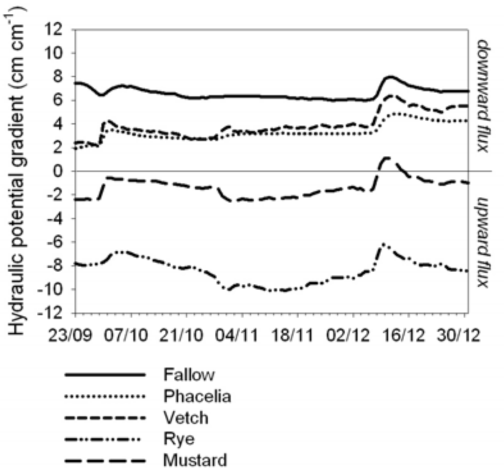
8.4 Discussion

8.4.1 Measurement methods and water balance

Direct measurements of evapotranspiration require weighable lysimeters. Beside the high costs of a lysimeter station, critical remarks have been made on the possibility to transfer the water flow regime inside a free draining lysimeter to an undisturbed field soil (Kastanek, 1995, Loiskandl et al., 1998). Hydrological field measurement sites, sometimes referred to as virtual lysimeters, focus on the continuous measurement of the water status under field conditions and the derivation of the not measured component, i.e. actual evapotranspiration, using the water balance equation (Hauer et al., 2003).

Several sources of error in measuring the system state variables have been remarked, e.g. disturbances during the installation of the measurement devices, the effective sensitivity of the installed sensor type to changes of the measured property or the accuracy of the algorithms used to transform the sensor signal into a physical unit, particularly when using default calibrations (Strauss-Sieberth and Loiskandl, 2005). Very critical in field measurement sites is the determination of flows through the lower system boundary by means of the Darcy-Buckingham law (Kastanek et al., 2001). These fluxes are quantified based on the measured hydraulic potential gradients. The driving gradients between 60 and 90 cm soil depth measured in 2005/06 are shown in figure 8.14.

Figure 8.14 Hydraulic potential gradients 2005/06 for calculation of lower boundary fluxes.



These measurements resulted in a seepage water flow out of the system under fallow, phacelia and vetch, while for rye and mustard capillary rise into the system was suggested. This may be related to a spatial trend in the soil properties. However the trend in the potential gradient does not exactly represent the spatial arrangement of the individual variants in the block where the measurement devices were installed, although rye and mustard were neighbouring variants separated by a three meter wide machinery strip from the other variants.

As a result of these differences in the hydraulic gradients, the water balance calculation resulted in higher evaporative losses particularly for rye which also showed the best agreement with the results suggested by the model (cf. Fig. 8.9).

For the first year when only water content was measured, the drainage term could only be estimated using a rough correction of the rainfall input variable. A measurement of the runoff term still was not possible during the two experimental years. As certainly runoff could be expected to differ between the treatments, the high values of bare soil evaporation estimated by the water balance in the wet autumn 2004 could result from an underestimation of runoff from fallow compared to the cover crops which was not reflected by the applied general correction method of effective rainfall.

In general a longer measurement period after installation of the sensors should be evaluated and a possible trend in the basic soil properties and its hydraulic impact at the lower boundary should be investigated to provide more reliability of the drainage flow estimates.

In our study two capacitance sensor types for water content measurement have been used since September 2005. Comparison of the two devices revealed a general shift between the absolute values of the sensor readings and also differences in the sensor reaction to soil wetting after a rainfall. While the horizontally installed sensors generally indicated a constant smooth decrease in soil water content below 10 cm over the cover crop vegetation period without any reaction to two higher rainfall events, the access tube sensors showed two clear peaks suggesting water infiltration to a depth of around 20 cm and consequently an increase in soil water content. The different depth of the wetting front after precipitation resulted in different values for the change in profile water storage over time in the water balance calculation. As all access tube sensors showed the same dynamics, an inaccurate installation is less probable than a general occurrence of preferential flow along the tube, particularly due to fissuring after the prolonged drought in autumn 2005.

A field calibration of the water content sensors is recommended using gravimetric reference samples to assure accurate absolute water content values. The observed differences in the water dynamics between the measurement devices as such seem to be related to the different sensor technology and installation procedures.

8.4.2 Model Calibration

The determination of hydraulic properties, i.e. the parameterization of an appropriate retention and conductivity function, for modelling the water flow dynamics in a field, is still a challenging topic in soil physics (Minasny and McBratney, 2002). Due to the lack of laboratory measurements on undisturbed soil samples, we applied different approaches making use of measured field data and available information on particle size distribution and bulk density for some indirect methods.

Measured field data pairs of water content and pressure head should accurately reproduce the observed water dynamics within the calibration range. However it is often difficult to get a unique parameter set for a retention model due to the narrow data range. This applies also to the present study where only little variability occurred during the measurement period. Another problem in estimating retention curves based on field measurements is hysteresis in the data. Field measurement data often do not fit to a predetermined retention model and the application of curve fitting based free models might describe the field situation more appropriately (Bitterlich et al., 2004).

Šimůnek et al. (1998a) presented an inverse method to fit the hydraulic properties to tension infiltrometer experiments. One advantage of this method is the parameterization of a hydraulic property model for the soil surface or a near surface layer. Our results based on cumulative infiltration data from spring 2006 generally suggested a high α value in the van Genuchten model for the upper soil layer. This is probably related to a strong influence of soil structure and the low air entry potential for a soil with a high contribution of structural macropores to the overall pore size distribution. A disadvantage of this method is its uncertainty in the dry range (Šimůnek et al., 1998b). Furthermore it reflects the high spatial and temporal variability of the measured structural domain resulting in a large variance of the derived hydraulic parameters.

Such structural influences on the soil hydraulic properties are commonly underestimated by indirect estimation procedures using pedotransfer functions (Pachepsky and Rawls, 2003). Several authors compared different PTFs to independent data sets and found high variability in the predicted parameters (e.g. Tietje and Hennings, 1993; Wagner et al., 2001). As a general rule, the PTF to be preferred should have been developed from a data base that includes the region of investigation or at least a region with a similar soil genesis. From the three PTFs used in the present study, HYPRES performed best to represent the time course of water content in the calibration period. Only in the upper soil layer the HYPRES based simulation was less accurate than that obtained with the other PTFs.

Additional calibration of the model by varying the hydraulic parameters to reduce RMSE could significantly improve the simulation results compared to the different standard parameterization methods. However, calibration is not only time consuming, but also may result in parameters out of any meaningful range. The knowledge about the variability of the parameters obtained by the different methods of parameterization helped to improve the efficiency of calibration, particularly in the upper layers where the field methods suggested high values of α and low values for n in the van Genuchten model that would not be expected based on the PTF estimates only. The calibrated hydraulic functions used for further simulation are similar to the curves derived from the field measurement data in the upper soil layers, while in the deeper layers the calibrated curves correspond to the HYPRES based estimates. The better performance of the PTF compared to the field estimates is probably explained by a reduced influence of structural features in deeper soil layers as well as the limited data range of the field measurements below 20 cm. However, when covering a broader soil moisture range, field data based methods seem more appropriate to derive parameters characterizing the hydraulic property functions of a field soil.

8.4.3 Simulation study

The general objective of applying a hydrological model to the field observations was to improve the understanding of the water flow processes under the given weather and soil conditions at the experimental site. After calibration, the simulated water content time series and cumulative evapotranspiration were compared to the measurement data and values derived from the water balance. A main result of the simulation study was the quantification of root water uptake of the cover crops in relation to the total evaporative losses as well as the analysis of differences in water balance components determining the soil moisture storage in the root zone at the seeding time of the subsequent crop.

8.4.3.1 Root water uptake vs. evaporation losses

The cumulative values of evapotranspiration from the water balance during the measurement period before winter (23 September – 20 December) ranged between 54 and 69 mm in 2004 and between 38 and 50 mm in 2005. Both, measurement data based calculations as well as simulated values of evapotranspiration, showed higher water losses under cover crops compared to fallow in case of dry weather conditions during the main cover crop growing period. In this case plant water requirements were sustained by deep profile depletion via roots and in this way water stress induced reduction of evaporative losses was retarded.

This capacity of a cover crop to explore a larger soil volume to satisfy its water requirements is reflected in the relation between actual and potential evaporation and transpiration respectively. Scenario analysis showed substantially lower stress reduction for the transpiration component in both years. An interesting difference between the two years occurred in the relation of soil evaporation from the cover cropped treatment in relation to fallow (E_{crop}/E_{fallow}= 0.51 in 2004 and 0.73 in 2005). The lower value in 2004 is related to the higher competition between plant water uptake and soil evaporation under the cover crop for the available water resources in the upper layers and thus a larger difference between fallow and cover crop soil evaporation. In 2005 the dry autumn resulted in a shift of root water uptake towards deeper soil layers and thus less competition between the two components of evapotranspiration in the dried surface layers. The scenario analysis for the virtual high yielding cover crop suggested a maximum difference to fallow of 27.6 % under such conditions being similar to the result found by Islam et al. (2006) in their modelling study.

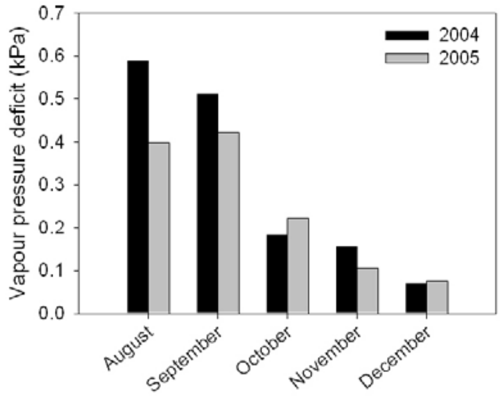
The simulated evapotranspiration of the investigated cover crops also reveals the proportion of transpiration of the total evaporative water losses (Tab. 8.5).

Table 8.5 Amount of transpiration relative to total evaporation losses.

	Average evapotranspiration	Phacelia	Vetch	Rye	Mustard	Scenario analysis
	mm				%	
2004	109.8	41.6	24.2	17.2	47.1	62.5
2005	100.3	20.0	52.6	29.0	31.8	51.3

The results show that cover crop transpiration in most cases accounts for less than half of the total evaporative losses with a maximum of 62.5 % for the high yielding cover crop scenario. This is obviously related to the decrease in the atmospheric demand in autumn when the fully developed plants reach their maximum water demand. Figure 8.15 shows the monthly mean vapour pressure deficit of the atmosphere which in October is less than half of the values in August and September for both years. As the main growing period of the cover crops generally falls between mid September and the end of October, a high amount of water losses to the atmosphere occurs via soil evaporation in late summer when there is still limited soil cover by the plant canopy. Thus a main concern in cover crop management in water limited environments should be focussed on a fast juvenile development and canopy closure to redistribute a higher amount of soil water towards transpiration.

Figure 8.15 Monthly mean vapour pressure deficit during the cover crop vegetation period.



The deviations we found between the modelled and measured cumulative evapotranspiration could have several reasons, both in the water balance based estimates as well as in the model parameterization. Possible sources of error in the measurement data have already been discussed before as well as difficulties in determining the parameters describing the hydraulic properties of a field soil. Additionally it has to be remarked that HYDRUS is a model oriented towards the analysis of hydrologic processes and no plant growth component is included explicitly beside root growth. Thus the potential evapotranspiration of the cover crops is a modelling input to be calculated elsewhere. The values used in this study were derived from the empirical FAO crop coefficient method based on soil cover measurements. The use of a plant growth model that determines potential crop transpiration and evaporation based on a more mechanistic approach could also improve the quality of the required crop input data.

8.4.3.2 Profile water storage

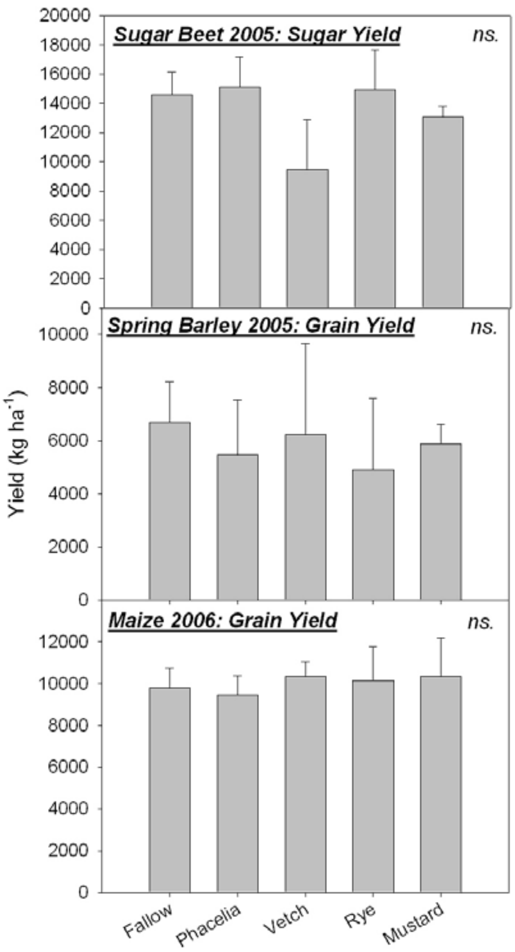
A particularly interesting observation from the measured water content data is the low difference in profile water storage in spring between the bare soil treatment and the cover crops. Assuming a common starting value for all treatments and correcting the data for the constant initial offset to eliminate sensor specific deviations, the mean absolute difference in profile water storage between the cover crops and fallow at the end of March was 3.7 % in 2004/05 and only 1.1 % in 2005/06. The modelled differences were 0.7 % and 1.0 %, respectively. The maximum additional depletion to a profile depth of 100 cm resulting from the “worst case” scenario analysis in spring 2005/06 was 2.8 %.

The related water balance components for the two extreme scenarios of a bare soil vs. a high yielding cover crop showed little difference in 2004/05 when the water requirements of the cover crop during the main growing period were satisfied by frequent rainfall. Both, soil evaporation and root water uptake, according to the assumed linear root distribution function, occurred mainly from the upper layers where sufficient water was available. A higher depletion of the deeper soil layers by the crop did not occur. In 2005/06 high precipitation in July resulted in a moist profile at the beginning of the simulation period. This is expressed by a high water flow through the lower boundary. The lack of rainfall between October and December caused a substantially higher depletion of the soil water storage from deeper profile layers by the cover crop while soil evaporation from the upper layers was limited for both, the fallow and cover crop scenario. Winter precipitation however refilled the depleted profile under the cover crop and reduced the differences towards spring, while the higher moisture content in the deeper layers under bare soil resulted in a higher amount of deep drainage during winter and spring.

Although there is still a visible soil moisture depletion in deeper soil layers, the simulation study showed that in the upper soil layers hardly any difference is to be expected in spring even in 2005/06. As the subsequent crop will depend particularly on soil moisture in these layers for germination and youth development, the additional cover crop water uptake should not have a negative effect during these early stages of the cash crop growth. This is in agreement with studies reporting even slightly higher soil moisture content near the soil surface under plant residues or cover plants (Wagner-Riddle et al., 1997). The sustained higher water content differences in the deeper layers in 2005/06 resulted mainly from the assumed stress compensation in the maximum depletion scenario. In case of low spring precipitation, such deep profile depletion could still affect the subsequent crop during later growing stages when it would depend on root water uptake from these deeper layers.

Indirectly the impact of the cover crops can be evaluated in terms of effects on the yield of the subsequent crop. Figure 8.16 shows the yield of the main crops after the cover crop treatments. On the plots where soil water content was monitored during the two experimental year, sugar beet and maize were grown as subsequent cash crops. For 2005 additionally the yield of spring barley is indicated after cover crops at the experimental replication where the soil water content had not been measured.

Figure 8.16 Yield of cash crops fallowing the cover crops *(ns.= non significant differences).*



The yields of none of the cash crops showed statistically significant differences. The comparatively low sugar yield in 2005 after vetch is probably explained by a non-homogeneous damage caused by frost in March 2005 to the young sugar beet plants as reflected by the high standard deviation in the vetch treatment.

In both experimental years the precipitation during summer was substantially higher than the long term average. In 2006, except July, the whole period between March and August was above the average monthly amounts of rainfall. Spring barley is considered to be hardly affected by cover crop induced water storage differences (Bodner, 2001), which furthermore were very low in spring 2005 as shown above for the measured site. Sugar beet and maize are more sensitive to water shortage. However, their main water requirements are at the time of flowering (Bramm et al., 1983) when sufficient rainfall occurred in both years.

Finally the scenario analysis revealed some effects on the infiltration process related to the differences in soil moisture distribution over the profile between a cover cropped and a bare soil. While soil evaporation tends to dry out the bare soil from the surface towards deeper layers, a canopy cover reduces the potential amount of water evaporating from the soil surface by “redistributing” a part of the atmospheric demand towards root water uptake from the entire profile according to the root density distribution. This explains a lower soil moisture in the upper centimetres of a bare soil and induces three basic effects on the infiltration dynamics: (1.) a lower hydraulic conductivity near the soil surface, (2.) a lower amount of water infiltrating to higher depth as a more depleted pore volume in the upper layers is first refilled and (3.) a pressure head gradient towards the dryer root zone in a cover cropped field. These changes result in a more intense water flux to the root zone of the cover crop and enhance the refilling of the soil layers previously depleted by root water uptake.

8.5 Conclusions

Four selected cover crops and a fallow control were analysed for differences in the soil water dynamics at a semi-arid site in Eastern Austria using the Richards equation based hydrological model HYDRUS 1D.

The comparison of water balance based evapotranspiration with estimates from the model revealed several sources of uncertainty to be taken into account in both the measurement data as well as the simulation results. A substantial influence of the sensor type could be shown on both, absolute water content values as well as the temporal changes in water content. Differences in the calculated drainage fluxes using observed hydraulic potential gradients and pedotransfer function based hydraulic conductivity estimates were also identified as a source of uncertainty. Although different methods were used for model parameterization, additional calibration of the hydraulic functions was necessary. In the structure influenced upper soil layers the field measurement based hydraulic property functions gave more reliable estimates compared to the indirect methods.

From the simulated scenario of a high yielding and deep rooting cover crop it can be concluded that potential higher evaporative water losses during the vegetation period between 6 % and 28 % could be expected compared to fallow. The maximum simulated transpiration in case of full plant cover however only accounted for 51 % to 62 % of the total evapotranspiration. Plant water uptake of the cover crops was substantially less than suggested by transpiration coefficients in literature, while a high amount of water is lost by soil evaporation in late summer. Thus fast canopy closure must be considered as an important growth trait of cover crops to conserve soil water in the system for plant uptake.

During both years the higher water storage depletion at the end of the cover crop vegetation period was reduced towards spring and tended to disappear in the upper soil layers. In 2005/06 the modelling results suggested a higher deep percolation during winter and spring under the bare soil treatment, while this water was conserved in the cover crop root zone due to a previously higher depletion.

Differences in the depth distribution of soil water content and pressure head as a result of soil surface cover and root water uptake induced a slightly higher infiltration flux to the root zone in a cover cropped field.

While the HYDRUS based worst case scenario analysis of water storage depletion assumed a high yielding cover crop in both years, under natural conditions there is an interaction between water availability and crop growth, i.e. soil moisture shortage is related to a low biomass growth. This natural “down-regulation” of water extraction must be considered when taking management decisions based on the biomass potential or transpiration coefficients given in literature, while evaporative losses from a non-covered surface should be taken into account.

The limited influence of the cover crops on the profile moisture content in spring is in agreement with no significant differences in the yield of the subsequent cash crops. From our results we therefore conclude that only under conditions of prolonged drought during the vegetation period of the main crop, the potentially higher water storage depletion from deeper profile layers after a cover crop can negatively influence the cash crop yield.

In a semi-arid region a water conserving cover crop management strategy should focus on the potential of the plants to reduce soil evaporation in their early growing stages when the crops themselves still have low water requirements, but could already provide a good surface cover. The characteristics of cover crop species for a semi-arid environment concerning biomass growth potential, juvenile development and rooting patterns must be defined in relation to the environmental priority of cover cropping. While erosion control would require a fast and complete soil cover, the mitigation of nitrate leaching needs a high biomass growth. Thus a combined analysis of the concrete environmental risk for society and the economic risk for the farmer of water storage depletion induced yield reductions are the basis for a sustainable management strategy. Soil-plant-atmosphere models including a more detailed representation of crop growth related to a hydrological model like HYDRUS can provide information for such an optimization of the cover crop management strategies in accordance with the agro-environmental objectives as well as the climatic and hydrological characteristics of the site.

8.6 Literature

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9 *General conclusion and outlook*

The objective of the present research study was to provide both scientific and practical contributions to our current knowledge on cover crop impacts on the soil water dynamics in semi-arid, water limited environments. The basis of the field study was a detailed assessment of the soil water status by means of a hydrological field measurement site for a bare soil in comparison to four commonly used cover crop species, i.e. phacelia, hairy vetch, rye and mustard, differing in their botanical families and root characteristics. Aboveground biomass, canopy coverage and several root parameters of the cover crop species were characterized in order to understand potential influences on the components of the water balance. Effects of the cover crops on evapotranspiration and infiltration were investigated in detail and potential impacts on soil water storage depletion were assessed within a general scenario analysis. Water flow processes were analysed using the FAO Dual Crop Coefficient approach and the hydrological model HYDRUS 1D.

Soil cover and root parameters were measured by image analysis. This technique allowed a high temporal resolution in soil cover assessment and provided the necessary parameters for the FAO model based evapotranspiration calculation. Groundcover measurements by image analysis were also used due to difficulties in non-destructive direct leaf area measurement of the cover crops in early development stages as well as for those crops where the plant habitus does not allow a reliable use of a portable leaf area meter even during later growth stages (vetch, rye). A calibration of ground cover measurements with destructively measured leaf area data could further improve the use of the image analysis method for both, evapotranspiration calculation and also light interception in the frame of crop growth analysis. Results from the image analysis based root measurements over two years showed a reliable characterization of the specific root parameters of the different species with this method. The labour-intensive root washing process, however, limits the possibilities of a higher temporal resolution for the description of the root growth process that would be important for water uptake studies to understand possible differences in depth penetration between the cover crops.

The comparison of measured and modelled water dynamics revealed some sources of uncertainty in both, field measured water balance components and the model parameterization. The main advantage of a field measurement site compared to a lysimeter is the limited soil disturbance and the possibility of using common machinery for tillage. A particular challenge in this measurement design is the precise quantification of upper and lower boundary fluxes. At the semi-arid experimental site with low deep drainage, the uncertainty related to fluxes through the lower system boundary will probably be less problematic for the calculation of actual evapotranspiration from the water balance equation. It seems more important to achieve a precise measurement of differences in surface runoff and the development of site specific calibration equations for the water content sensors for the calculation of the evaporative fluxes from the measured water balance data. Field calibration of water content sensors – when combined with some pressure head and infiltration data - could also be used to derive site specific parameters for the retention and hydraulic conductivity functions in hydrological simulation models. The precise parameterization of these hydraulic property functions is a main problem for an accurate model based analysis of water dynamics. Thus a proper experimental design for field calibration of sensors could help to achieve high precision in both, absolute values of the measurement data and model parameterization.

The two years evaluated in this study were characterized by very distinct rainfall distribution over the cover crop vegetation period with the first year showing evenly distributed precipitation during the main growing period of the plants and the second year a prolonged drought in autumn after a wet late summer. This variability provides the possibility to derive some broader conclusions from the results obtained so far at the experimental site in relation to the questions and hypotheses formulated initially and to some aspects of cover crop growthe performance under semi-arid conditions *(cf. chapter 5)*.

Cover crop canopy cover dynamics, aboveground biomass and rooting patterns were strongly influenced by differences in rainfall distribution over the vegetation period. Mustard showed the highest stability to variable climatic conditions with a fast germination and high final soil coverage also under dry conditions, a high root biomass with a strong tap root and an intense formation of fine lateral roots. Vetch was most sensitive to soil moisture shortage during germination and early growth leading to a high inter-annual variability in aboveground biomass and soil cover. Phacelia was susceptible to drought during the later growing stages, resulting in an early reduction of living soil cover in late autumn. Rye had the lowest aboveground biomass and a maximum soil cover below 60 % even under favourable growing conditions. A major advantage of the rye cover crop was its high root to shoot ratio and an intense and homogeneous rooting pattern in spite of a limited aboveground biomass growth. Vetch had the lowest root density in the main rooting zone. However its root distribution is very homogeneous in the horizontal as well as in the vertical direction and shows a sensitive reaction to dry conditions with increasing root density in deeper layers, thus providing sufficient water even for a high aboveground biomass. The root density of phacelia on the contrary is very high near the shoot base, but decreases substantially in both the vertical and the horizontal direction.

<u>HYPOTHESIS 1: EVAPOTRANSPIRATION</u> *(cf. chapter 6)*

Water losses to the atmosphere via soil evaporation and plant transpiration are passive processes, driven by the gradient in water potential between the soil and the atmosphere with the plant inserted in this continuum. For cover crop potential evapotranspiration, the low saturation vapour deficit of the atmosphere during the period of maximum plant transpiration of the fully developed cover crop canopies is a natural limiting factor. Main potential water losses during the cover crop vegetation period occur during later summer when the plants have still less water demand and limited access to water resources in deeper profile layers. All evaporative losses in this period of initial cover crop growth are concentrated to the surface near layers where soil evaporation and root water uptake – proportional to root density, concentrated in the upper soil layers too – compete for the available water resources. Cover crops with fast soil coverage thus can be considered as more competitive because a lower proportion of the available water resources will be lost unproductively. In the later growing stages cover crops can take advantage of their capacity to access soil water from deeper layers in years of lacking autumn precipitation to refill the upper soil layers. The low atmospheric demand however reduces the potential impact of this increased deep profile depletion. The measured differences in evapotranspiration for such a scenario were +9.2 % and the modelled worst case +27.6 % compared to fallow. These results are in agreement with values given in literature which indicate potentially higher water losses up to 30 % for cover crops. When separating the transpiration component, it could be shown that plant water uptake accounted between 20 % and 50 % of total evapotranspiration only. Relating this amount of transpiration to the plant biomass, transpiration coefficients ranged between 160 to 420 $l\ kg^{-1}$ being substantially lower than it would be expected from values for main crops. For the higher transpiration values, model analysis suggested a substantial water uptake from deep profile layers by water stress compensation that was implemented as a new component in the FAO Dual Crop Coefficient model. Due to the simple budget approach for the daily water balance calculation in the FAO model, no capillary rise is considered. The HYDRUS simulation showed that upward capillary fluxes will result in additional water supply to the roots from deeper soil layers which indicated that there is probably less need for stress compensating mechanisms of the plants as suggested by the FAO model.

<u>HYPOTHESIS 2: INFILTRATION</u> *(cf. chapter 7)*

Soil structure, in contrast to texture, is a dynamic property with a high small scale variability both in space and time. Its instantaneous state is the result of permanent processes of formation, stabilization and decomposition of aggregates and the related voids between them. The association of the primary particles towards higher hierarchical units is mediated by several structure forming agents. The initial clustering is influenced by textural site characteristics themselves, particularly clay type and content, as well as the ionic state of the sorption complex. At higher hierarchical units wetting and drying cycles, freezing and thawing cycles, plant roots and residues as well as a variety of soil organisms influence the structural dynamics. The short term management effect of cover crop plants on infiltrability and hydraulic conductivity in the structural macro-pore space on a sloping field was therefore largely displaced by other factors determining temporal and spatial variability and only accounts for about 10 % of the total variability of these properties. Particularly shrinking cracks due to wetting-drying cycles on the bare soil surface induced the formation of large macro-pores leading to a high hydraulic conductivity particularly near saturation. In a dry autumn, this increased hydraulic conductivity up to around 60 % compared to a soil covered by green manure crops. Such pores, however, are of limited stability. Statistical analysis with a mixed model covariance approach allowed us to show that this is expressed in a significantly lower relative increase of water conducting porosity over winter in a bare soil compared to cover crops. It reveals the stabilising effect of the plants in the temporal dynamics of pore formation and collapse and the potential management effect of cover crops within the variety of natural structure inducing factors.

HYPOTHESIS 3: WATER STORAGE DEPLETION *(cf. chapter 8)*

The change in profile water storage between cover crop seeding in late summer and seed bed preparation for the succeeding cash crop in early spring is a function of losses and inputs according to the water balance equation. A model based scenario analysis for a water intensive cover crop showed that only in case of a prolonged dry period in autumn, the higher evaporative losses will induce water storage depletion. But even in such a worst case, the upper layers of the soil profile were refilled entirely by winter precipitation, while higher drainage losses occurred below the root zone under the bare soil. This reduced the differences in soil moisture storage to a depth of 100 cm between a cover crop and fallow from about -7 % during cover crop growth to -2.8 % in spring. The water content profile resulting from plant water uptake distributed over the whole root zone differed from the bare soil where the surface near evaporation layer was more depleted. This induced a higher infiltration flow to deeper layers under the cover crops, contributing to equilibrate water content differences to bare soil in the cover crop root zone. These model calculations, however, do not consider possible structural effects in the macropore range, e.g. preferential water flow in shrinking cracks. According to the modelling results, differences in germination and early development of the following main crop due to water content differences in the upper soil layers are not to be expected, even under a worst case scenario where the potentially higher water storage depletion until spring is found only in deep soil layers. Significant yield differences might only occur in case of continued drought during later growing stages of the cash crop when it depends on such deep profile water resources. However, in both experimental years this was not the case in our study and no yield differences occurred in sugar beet, maize and spring barley.

Translating these findings into practical implications for cover crop management in semi-arid regions, we can draw the following conclusions:

(i) *Feasibility under semi-arid conditions:* Cover cropping is generally feasible under semi-arid conditions in Central Europe, where potential atmospheric water losses during the main cover crop growth in autumn are low. The probability of soil water depletion to an extent having negative impacts on the cash crops' yield is therefore low.

(ii) *Definition of the environmental goal:* Cover cropping is an agro-ecological management instrument for soil and groundwater protection. The main environmental objectives are the reduction of nitrate leaching, the avoidance of soil erosion and the improvement of the humus balance. A precise definition of the central environmental goal(s) within a site specific risk-benefit analysis will allow the adaptation of the management and the selection of adequate species for a water limited agricultural region.

(iii) *Adaptation of the management to the goal:* While groundwater protection and green manuring requires the maximization of the plant biomass, erosion control must guarantee a fast and complete soil cover. The first objectives will be optimized by a management system with permanently living plants which continue growth after winter, the second objective will be satisfied also by a mulch cover of cover crop plants clipped before winter or killed by frost. The first management goal implies higher risk of water storage depletion under water limited conditions. However at such sites the potential crop biomass growth is frequently reduced by drought and main attention should be put on the related increase of unproductive soil evaporation from poor cover crop stands. Therefore a central management priority for water efficient cover cropping is the reduction of unproductive evaporation losses particularly in late summer by providing optimum soil conditions for germination leading to a fast development of a closed canopy.

(iv) *Selection of the plant species:* Maximising nitrate uptake requires high rooting depth and water extraction which necessarily implies highest risk for profile depletion (mustard). If the reduction of nitrate leaching to groundwater is not the priority goal, plant species with an intense rooting of the upper layers with less root development to depth (phacelia) should be preferred. A mixture of species for fast soil cover (mustard) with plant species for an intense (fine) rooting in the upper layers (phacelia) can optimize soil structure improvement and minimize the risk of moisture depletion. Rye was found to have a high root biomass and density, but did not provide a satisfactory ground cover for competing successfully with unproductive evaporation losses as required for water limited conditions. Winter-hard hairy vetch can be considered an optimum green manure plant with potentially high organic input. Susceptibility to water shortage during germination and early growth however may delay the development of a closed canopy. For purposes of groundwater protection it should certainly be used in mixture with non-legume species.

Our results revealed those components of the water balance with major impacts from cover crops and where most effects from management can be expected. Some short term effects of plant-soil structure interactions on hydraulic properties in macro-pore stabilization could be shown. Effects related to modifications in the carbon cycle under long term green manuring certainly require further observations of system changes over several years. Furthermore some improvements in the quantification of the water balance components were identified and will be implemented, particularly in site specific sensor calibration, field retention curve determination and runoff measurement.

Managing soil water will become an increasingly important topic in both environmental sciences and agriculture. The complex soil structure dynamics and the related hydraulic properties, which are a key element in human influences on the soil functions – both positive and negative ones – are still a wide field for interdisciplinary, basic and applied, research. It requires the integration of a range of methods, from field measurements to the development of new modelling approaches, for describing the mechanics and trends in a dynamic system. We think that our study has provided some elements and ideas for further efforts to deepen our insights in the soil black box and improve a knowledge based sustainable soil and water management in agriculture.

10 *Schlussfolgerungen und Ausblick*

Ziel der vorliegend Arbeit war es, sowohl wissenschaftliche als auch praktische Beiträge zum gegenwärtigen Kenntnisstand über Zwischenfruchteinflüsse auf die Bodenwasserdynamik im semi-ariden Gebiet zu erarbeiten. Die Grundlage der Feldstudie war die detaillierte Messung des Wasserstatus im Boden über eine Feldmessstelle bei vier Zwischenfrüchten (Phacelia, Winterwicke, Grünroggen, Senf) und Schwarzbrache. Die oberirdische und Wurzelbiomasse, Bodenbedeckung und verschiedene Wurzelparameter der Zwischenfrüchte wurden gemessen, um ihre Auswirkungen auf die Komponenten der Wasserbilanz zu untersuchen. Besonderes Augenmerk wurde auf Einflüsse auf die Evapotranspiration und die Infiltration im Makroporenbereich gelegt. Die potentiellen Auswirkungen auf den Bodenwasserhaushalt wurden mittels Szenarioanalysen abgeschätzt. Zur Analyse der Wasserflüsse wurden die FAO-Pflanzen-Koeffizienten-Methode sowie das hydrologische Modell HYDRUS 1D verwendet.

Bodenbedeckung und Wurzelparameter wurde mit Hilfe von Bildanalyseverfahren gemessen. Diese Technik erlaubte eine hohe zeitliche Auflösung der Quantifizierung des für die Evapotranspirationsberechnung mittels der FAO-Methode notwendigen Bodenbedeckungs-Parameters. Die Verwendung der Bildanalyse ergab sich auch aus Schwierigkeiten einer nicht-destruktiven Blattflächenmessung der Zwischenfrüchte während der frühen Wachstumsstadien sowie für jene Pflanzen (Winterwicke, Roggen), deren Habitus die in-situ Blattflächenbestimmung problematisch macht. Eine Kalibration der bildanalytischen Bodenbedeckungsmesswerte könnte anhand destruktiver Blattflächendaten erfolgen, um diese sowohl für die Evapotranspirationsberechnung als auch die Analyse der Strahlungsnutzung in Zusammenhang mit Fragen der Assimilation zu verwenden. Die ebenfalls mit Bildanalyse in beiden Jahren gemessenen Wurzelparameter zeigten, dass diese Methode eine gute Erfassung der charakteristischen Zwischenfruchtmerkmale erlaubte. Die arbeitsintensive Probenvorbereitung stellt dabei jedoch eine Beschränkung für eine höhere zeitliche Auflösung dar, um auch das Wurzelwachstum zu beschreiben. Die Kenntnis möglicher Unterschiede zwischen den Pflanzenarten insbesondere in der Dynamik des Tiefenwachstums der Wurzeln wäre gerade für Fragen der Wassernutzung in Trockengebieten wichtig.

Der Vergleich der gemessenen und modellierten Bodenwasserdynamik zeigte mögliche Unsicherheiten, sowohl in den gemessenen Wasserbilanzkomponenten als auch in der Modellparametrisierung. Der hauptsächliche Vorteil der Feldmessstelle im Vergleich zu einem Lysimeter liegt in der geringen Störung des Bodens und der Möglichkeit einer praxisüblichen Bodenbearbeitung. Die wesentliche Herausforderung bei dieser Messanordnung ist die präzise Bestimmung der Wasserflüsse durch die obere und untere Systemgrenze. Für den semi-ariden Versuchsstandort mit sehr geringer Tiefensickerung ist jedoch eine eher geringe Auswirkung eines möglichen Fehlers in der Quantifizierung der Sickerwassermenge auf die Zielgröße der aktuellen Evapotranspiration zu erwarten. Die möglichst genau Messung des Oberflächenabflusses in den einzelnen Varianten sowie eine standortspezifische Kalibration der Wasseranteilssensoren scheint dagegen wichtiger zu sein, um aus den Feldmessdaten exakt die Verdunstungsverluste am oberen Rand zu errechen. Daten einer Feldkalibration könnten bei geeigneter Versuchsanordnung, über die Verbindung mit punktuellen Wasserspannungsdaten und Infiltrationsmessungen, einen doppelten Nutzen haben. Neben präzisen Absolutwerten des Bodenwasseranteils, könnte eine Ableitung der Parameter der Retentions- und Leitfähigkeitsfunktion für den Standort erfolgen, deren Bestimmung ein zentrales Problem für eine zuverlässige Analyse der Wasserdynamik mit Hilfe von Simulationsmodellen darstellt.

Die zwei Untersuchungsjahre zeichneten sich durch sehr unterschiedliche Niederschlagsverteilung während der Zwischenfruchtvegetationsperiode aus. Das erste Jahr war durch gleichmäßig verteilte Niederschläge charakterisiert, während es im zweiten Jahr zu einer langen Trockenperiode im Herbst kam. Diese Variabilität in den Feuchtebedingungen während der beiden Jahre erleichtert es, einige verallgemeinerbare Schlussfolgerungen im Bezug auf die anfänglich aufgestellten Hypothesen und die Eignung der unterschiedlichen Begrünungsarten für einen semiariden Standort *(siehe Kapitel 5)* zu ziehen.

Die Zwischenfrüchte wurden in ihrem Wachstumsverlauf stark durch die Niederschlagsverteilung während der Vegetationsperiode beeinflusst. Senf zeigte die höchste Stabilität gegenüber den variablen Feuchteverhältnissen mit einem in beiden Jahren sicheren Feldaufgang, einer hohen und raschen Bodenbedeckung sowie einer hohen oberirdischen Biomasse. Neben der starken Pfahlwurzel zeichnete er sich auch durch eine intensive Seitenwurzelbildung aus. Die Winterwicke dagegen war besonders während der Keimung und Jugendentwicklung sensibel gegenüber spätsommerlicher Bodentrockenheit und zeigte eine hohe Jahresschwankung in der oberirdischen Biomassebildung. Bei Phacelia trat eine stärkere Reduktion der Bodenabdeckung mit grünen Blättern im entwickelten Bestand im Herbst infolge Trockenstress bedingter Welkeerscheinungen auf. Roggen bildete die geringste oberirdische Biomasse aus und erreichte auch unter optimalen Feuchteverhältnissen unter 60 % Bodenbedeckung. Der Vorteil von Roggen war seine intensive Durchwurzelung des Oberbodens trotz geringer oberirdischer Biomassentwicklung. Winterwicke wies die geringste Wurzeldichte auf. Die Wurzelverteilung war jedoch sowohl horizontal als auch vertikal sehr homogen. Trockenbedingungen führten zu einer Erhöhung der Wurzeldichte in tieferen Schichten, was die Bildung einer hohen oberirdischen Biomasse trotz geringer Durchwurzelungsdichte erlaubte. Phacelia dagegen zeigte eine sehr intensive Durchwurzelung nahe der Sprossbasis, die jedoch rasch sowohl in horizontale als auch vertikale Richtung abnahm.

<u>HYPOTHESE 1: EVAPOTRANSPIRATION</u> *(siehe Kapitel 6)*

Die Wasserflüsse im Boden-Pflanze-Atmosphäre Kontinuum sind ein passiver Prozess, der durch den Potentialgradienten zwischen Boden und bodennaher Atmosphäre angetrieben wird, in den sich die Pflanze einschaltet. Damit werden die potentiellen Wasserverluste einer Zwischenfrucht, deren Hauptwachstumszeit im Herbst liegt, durch das atmosphärische Verdunstungspotential beschränkt. Die Hauptverluste fallen auf den Spätsommer, wenn die Zwischenfruchtpflanzen jedoch erst einen geringen Wasserbedarf und wenig Zugang zu tiefer liegenden Wasservorräten im Boden haben. Die Verdunstungsverluste in dieser frühen Wachstumsphase der Zwischenfrüchte sind auf die oberen Bodenschichten konzentriert, wo unproduktive Bodenevaporation und Wurzelwasseraufnahme um die verfügbaren Wasservorräte konkurrieren. Zwischenfrüchte mit rascher Bodenabdeckung sind damit konkurrenzfähiger, indem sie den unproduktiven Wasserverlust von der Bodenoberfläche verringern. In späteren Wachstumsphasen können Zwischenfruchtpflanzen über das Wurzelwachstum tiefere Bodenschichten ausschöpfen, vor allem wenn die oberen Bodenschichten austrocknen, auf die sich die Wasseraufnahme aufgrund der Wurzelverteilung im Allgemeinen konzentriert. Das geringere Verdunstungsdefizit limitiert jedoch die Profilausschöpfung in der späteren Vegetationsperiode. In einem trockenen Herbst lagen die höheren Verdunstungsverluste von Zwischenfrüchten bei +9,2 % im Vergleich zu Brache. Die Szenarioanalyse brachte eine maximale Differenz von +27,6 % für tief wurzelnde Zwischenfrüchte. Diese Ergebnisse stimmen mit bisherigen Erkenntnissen in der Literatur überein. Es zeigte sich jedoch, dass nur etwa 20 % bis 50 % der gesamten Evapotranspiration auf die Pflanzenverdunstung fallen. Dies führt zu einer hohen Wassernutzungseffizienz von Zwischenfrüchten im Vergleich zu Hauptfrüchten mit Transpirationskoeffizienten zwischen 160 und 420 $l\ kg^{-1}$. Die Transpirationswerte am oberen Limit wurden in Rahmen einer Modellanalyse auf Wasserstresskompensation zurückgeführt, die als neue Komponente in das FAO Pflanzenkoeffizienten-Modell integriert wurde. Dabei ist jedoch zu berücksichtigen, dass die Wasserbilanzberechnung des FAO Modells auf einem einfachen Budgetansatz beruht und keinen Kapillaraufstieg berücksichtigt. Die HYDRUS-Simulation zeigte solche kapillare Wassernachlieferung aus tieferen Schichten zu den Wurzeln, was darauf hinweist, dass möglicherweise nur ein geringerer Grad der Stresskompensation für die Wasserversorgung der Pflanzen notwendig war.

HYPOTHESE 2: INFILTRATION *(siehe Kapitel 7)*

Die Bodenstruktur ist im Gegensatz zur Bodentextur eine dynamische Eigenschaft mit hoher kleinräumiger sowie zeitlicher Variabilität. Ihr momentaner Zustand ist das Ergebnis ständiger Prozesse der Bildung, Stabilisierung und des Zerfalls von Aggregaten und damit verbundener Porenräume. Die Zusammenfügung von Primärteilchen zu höheren hierarchischen Einheiten wird durch verschiedene strukturbildende Faktoren vermittelt. Die anfängliche Verbindung zu Clustern ist stark von der Textur selbst beeinflusst, vor allem dem Tongehalt und der Art der Tonminerale, sowie vom Ionenbesatz des Sorptionskomplexes. Höhere hierarchische Einheiten sind das Ergebnis von Feuchte-Trockenzyklen, Frost und Tau, Pflanzenwurzeln, organischen Rückständen und der Aktivität der Bodenlebewesen. Kurzfristige Managementeffekte von Zwischenfrüchten auf die Infiltration und hydraulische Leitfähigkeit im strukturbeeinflussten Makroporenraum waren daher stark überlagert von anderen Faktoren, die die räumliche und zeitliche Variabilität der untersuchten Größen beeinflussten. Der Zwischenfruchteinfluss machte weniger als 10 % der Gesamtvariabilität aus. Besonders Schrumpfrisse in der Brache wurden als wesentlich für deren hohe Leitfähigkeit diskutiert, die besonderes im trockenen Herbst etwa 60 % über jener der Zwischenfrüchte lag. Diese Risse zeigten jedoch geringe Stabilität über Winter. Mittels statistischer Analyse anhand eines gemischten Kovarianzmodells konnte gezeigt werden, dass die Brache einen signifikant geringeren Zuwachs in der hydraulischen Leitfähigkeit über Winter aufwies. Dies wurde auf den stabilisierenden Effekt der Pflanzendecke in der zeitlichen Dynamik aus Porenneubildung und -kollaps zurückgeführt und zeigt die Möglichkeiten der Strukturstabilisierung durch Zwischenfrüchte bereits für kurze Zeiträume der Begrünung einer Ackerfläche.

HYPOTHESE 3: BODENWASSERAUSSÖPFUNG *(siehe Kapitel 8)*

Die Veränderung des Profilwassergehalts zwischen Aussaat der Begrünung im Spätsommer und Umbruch im folgenden Frühjahr ist eine Funktion aus Input- und Verlustgrößen entsprechend der Wasserbilanzgleichung. Die Modellanalyse einer wasserintensiven, tief wurzelnden Zwischenfrucht zeigte, dass nur nach einem besonders trockenen Herbst mit erhöhter Wasseraufnahme der Begrünung aus tiefen Bodenschichten eine deutlich geringere Profilwasserspeicherung im Vergleich zur Brache zu erwarten ist. Über Winter werden diese Unterschiede in den oberen Bodenschichten weitgehend ausgeglichen. Die Brache zeigte auch höhere Wasserverluste durch Tiefenversickerung unter die Wurzelzone. Die Profilwassergehaltsunterschiede bis zu einer Bodentiefe von 100 cm betrugen -7 % im Herbst und reduzierten sich bis ins Frühjahr auf -2.8 %. Das Bodenfeuchteprofil zeigte ebenfalls Unterscheide. Die Wasserverluste über Evaporation trockneten bei Brache besonders die oberste Schicht aus, während unter der Begrünung die Wasserentzüge über das gesamte Profil verteilt waren und die oberste Schicht feuchter blieb. Dies führte zu Unterschieden im Infiltrationsverhalten, mit höheren Flüssen in die Wurzelzone der Zwischenfrüchte, die wiederum eine Angleichung des Wasseranteils zur Schwarzbrache bewirkten. Dabei werden vom Modell jedoch keine Bodenstruktureffekte wie Makroporenfluss über Schrumpfrisse berücksichtigt. Da die Folgefrucht für Keimung und Jugendentwicklung besonders vom verfügbaren Bodenwasser in den oberen Schichten abhängt, ist in dieser Entwicklungsphase der Hauptfrüchte keine negative Zwischenfruchtwirkung zu erwarten. Nur im Fall verlängerter Frühjahrstrockenheit können Wassergehaltsunterschiede in tieferen Profilschichten die Wasserversorgung der Hauptfrüchte einschränken, wenn diese in ihren späteren Wachtumsperioden bereits Zugang zu diesen Wasservorräten hätten. In den beiden Jahren der Feldstudie war dies jedoch nicht der Fall und es wurden keine Unterschiede im Hauptfruchtertrag von Zuckerrübe, Mais und Sommergerste festgestellt.

Folgende Schlussfolgerungen für das praktische Zwischenfruchtmanagement in semi-ariden Gebieten wurden aus diesen Erkenntnissen gezogen:

(i) *Machbarkeit des Zwischenfruchtbaus unter Wasser limitierten Bedingungen:* Für die semi-ariden Gebiete Mitteleuropas ist eine breite Nutzung von

Zwischenfrüchten in der Fruchtfolge möglich. Die geringen atmosphärischen Verdunstungsdefizite im Herbst reduzieren den Zwischenfruchtbedingten Wasserverlust. Die Wahrscheinlichkeit von Ertragseinbußen aufgrund erhöhter Bodenwasserausschöpfung ist gering.

(ii) *Definition des Umweltziels:* Zwischenfruchtbau als Agrarumweltmaßnahme zielt auf Boden- und Grundwasserschutz durch Verringerung der Nitratauswaschung, Einschränkung der Bodenerosion und Verbesserung der Humusbilanz ab. Eine genaue Definition des zentralen Umweltziels der Begrünung für den jeweiligen Standort erlaubt eine Risiko-Nutzenanalyse und die darauf beruhende Anpassung des Managements sowie der Sorten an Wasser limitierte Bedingungen.

(iii) *Anpassung des Managements*: Grundwasserschutz und Humuszufuhr verlangen eine Maximierung des Aufwuchses, während Erosionsschutz vor allem eine rasche und vollständige Bodenabdeckung erfordert. Die erste Zielsetzung wird durch Zwischenfrüchte mit hohem Wachstumspotential und möglichst langer Vegetationszeit (winterharte Zwischenfrüchte) optimiert, zweitere wird auch durch eine Mulchauflage einer eingekürzten oder abgefrosteten Begrünung ausreichend erfüllt. Das erste Managementziel ist demnach mit einem höheren Risiko für die Bodenwasserausschöpfung verbunden. Unter Wasser limitieren Bedingungen wird jedoch der tatsächliche Aufwuchs meist eingeschränkt und die Bestände sind lichter, womit die unproduktiven Verluste über Bodenevaporation steigen. Das Erreichen eines raschen Feldaufgangs durch optimale Saatbeetbereitung und damit die rasche Verringerung der Bodenverdunstung durch eine geschlossene Pflanzedecke ist eine Managementpriorität unter semi-ariden Bedingungen.

(iv) *Auswahl der Pflanzenart:* Die Maximierung der Bodennitrataufnahme in die Pflanze erfordert tiefwurzelnde Arten, die einen hohen Wasserentzug haben (Senf). Wenn die Verringerung der Nitratverlagerung nicht die Umweltpriorität ist, sollten unter semi-ariden Bedingungen Pflanzen gewählt werden, die besonders in der Oberkrume eine intensive Durchwurzelung zeigen (Phacelia) und damit die Bodenstruktur fördern. Eine Mischung aus schnell wachsenden Bodendeckern (Senf) und Pflanzen mit intensiver (Fein)Bewurzelung im Oberboden (Phacelia) ist für einen semi-ariden Standort besonders geeignet. Grünroggen zeigt zwar ebenfalls eine intensive Wurzelmasse und –dichte im Oberboden. Die geringe Bodenbedeckung im zweijährigen Versuch machte ihn jedoch wenig konkurrenzfähig gegen erhöhte unproduktive Evaporationsverluste. Winterwicke ist eine hervorragende Gründüngungspflanze mit hohem Wachstumspotential, braucht jedoch besonders gute Keimungsbedingungen. Für den Grundwasserschutz ist sie in jedem Fall mit einer Nicht-Leguminose zu mischen.

Unsere Ergebnisse zeigten, welche Komponenten der Wasserbilanz hauptsächlich durch die Zwischenfrüchte beeinflusst und wo durch das Management am besten eingegriffen werden kann. Es wurden auch Auswirkungen von Pflanze-Bodenstruktur-Wechselwirkungen auf die Dynamik der hydraulischen Eigenschaften im Makroporenbereich gezeigt. Zu erwartende langfristige Effekte einer mehrjährigen Begrünung über die Beeinflussung des Humushaushaltes erfordern eine weitere Beobachtung der Systemveränderungen. Verbesserungsmöglichkeiten in der quantitativen Wasserhaushaltsbeurteilung ergeben sich besonders im Bereich der Integration von Messeinrichtungen für den Oberflächenabfluss, der feldspezifischen Sensorkalibration und der Bestimmung von Feldretentionskurven für die Wasserhaushalts-Modellierung.

Das Management des Bodenwassers wird in Zukunft ein zentrales Thema der Agrar- und Umweltwissenschaften sein. Die komplexen und dynamischen hydraulischen Eigenschaften im Bodenstrukturbereich unterliegen dabei sicher bedeutender Einflussmöglichkeiten durch das Management – sowohl positiver als auch negativer – und sind daher ein noch weites Feld für interdisziplinäre Forschung. Die Integration von Ergebnissen aus Feld- und Labormessungen bis hin zu neuen Modellierungsansätzen sind notwendig, um die Mechanik und Trends eines dynamischen Systems wie dem Boden zu erfassen. Wir hoffen, dass unsere

Arbeit einige Element und Ideen zur Erfassung der Prozesse in der Black-Box Boden beigetragen hat, da deren Verständnis die Grundlage einer nachhaltigen Boden- und Wasserbewirtschaftung durch die Landwirtschaft ist.

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2003 – present

PhD Student at the Institute of Agronomy and Plant Breeding.

PhD-Thesis on: Analysis and modelling of cover crop influences on soil physical parameters and the water balance

3. Research Emphasis

Research focus is on the impact of plant production on soil water dynamics and soil physical quality. Particular attention lies on plant/root-soil structure interactions of different agricultural management tools like cover cropping, crop rotation and tillage and temporal changes of soil hydraulic properties in the soil structural domain. Experience has been gathered in automated soil hydraulic measurement sites and different soil physical methods. Knowledge on modelling water dynamics and plant growth for long term assessment of management induced changes has been acquired.

4. Projects

2003-2004**:** *BOWAFU – Analysis and Modelling of Crop Rotation Effects*

2004-present: *Water Balance of Cover Crops*

2004 – present: Cooperation in soil water and soil physical measurement in the Project: *Agronomic and environmental impacts of different tillage systems*

14 List of publications

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Matejka, F.: 13th International Poster Day, Transport of Water, Chemicals and Energy in the Soil-Plant-Atmosphere System, 10.11.2005, Bratislava, 45-47.

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