Doctoral Thesis

Multi criteria evaluation of land restoration for agricultural use

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Multi Criteria Evaluation of Land Restoration for Agricultural Use

A dissertation submitted to the
SWISS FEDERAL INSTITUTE OF TECHNOLOGY ZURICH

For the degree of
DOCTOR OF SCIENCES

presented by

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2008
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Soil restoration on former construction or exploitation sites or deposits is of increasing importance. When soil is restored for agricultural land use, the primary goal is to re-establish a high and sustainable soil quality for plant productivity. At the beginning of the process after excavation and refilling, restored soils are mechanically labile. Inadequate restoration procedures and over-use of restored soils often lead to over-compaction, water-logging and insufficient aeration, which are difficult to remediate. Hence, good practices for soil restoration and subsequent management have been proposed in official guidelines. However, there is a lack of methods suited for practical applications to monitor and assess the physical quality of restored soils for plant production and their sensitivity to compaction.

Addressing the need for an improved evaluation framework for restored soils, the specific objectives of this study were (1) to develop a methodology to assess the quality of restored soils and to compare this methodology with existing approaches, (2) to propose a simple indicator for the assessment of physical soil quality, and to compare the critical limits of this indicator with existing soil quality indicators, (3) to monitor the development of the physical quality and the mechanical stability of soil that had been restored according to pertinent regulations and (4) to develop multiple linear regression functions to determine the soil mechanical parameters precompression stress and the compaction index from basic soil properties.

A fuzzy logic expert system for the evaluation of the physical quality of soil for plant production was developed and applied on 10 restored and 10 adjacent non-restored soils. Physical soil quality decreased or remained unchanged after soil restoration at most investigated sites. Only two horizons showed improved soil conditions after restoration. The fuzzy logic expert system is based on the statements of a group of soil scientists relating physical soil quality for plant production to packing density, penetration resistance, air capacity and saturated hydraulic conductivity. The
participating experts were asked to express their own evaluation standards in fuzzy sets and their judgements were fairly consistent. Although the interactions between parameters were modelled in different ways by them it was possible to incorporate most of the experts’ opinions in a consistent rule base. The fuzzy logic expert system for the assessment of physical soil quality of restored soils gave very plausible results and the assessments matched well with two other indicators of the physical quality of soil, the least limiting water range and the so-called S-parameter (i.e. the slope of the soil water retention curve at the inflection point). The fuzzy logic approach proved to be a very flexible and appropriate tool for modelling the dependence of physical soil quality on the considered input parameters.

A literature study was conducted on optimum and limiting bulk densities of soils of different textures for plant production. The results suggest that both optimum bulk density and limiting bulk density can be satisfactorily derived by pedotransfer functions from general soil properties such as clay and silt content. Optimum and limiting values of bulk density can be transformed into optimum and limiting packing density values which are less dependent on soil texture. A packing density value of 1.70 is suggested as a threshold value that divides between optimum and limiting conditions for root and plant growth. Two other soil properties were identified as indicators of the state of compaction of a soil: the least limiting water range and S-parameter. The three indicators were measured or calculated by means of pedotransfer functions in 59 soil horizons sampled in Northern Switzerland. Packing density (PD), least limiting water range (LLWR) and S-parameter were linearly correlated. The results further indicate that the critical limits for root and crop growth, that were established for PD, LLWR and S-parameter, functionally correspond to each other.

In a field study on a soil that was freshly restored according to pertinent guidelines we monitored over three years the regeneration of some physical soil quality indicators (bulk density, coarse porosity and penetration resistance) and the development of indicators of mechanical stability (precompression stress and compression index). The comparison of the measurements with literature values indicated that the state of compaction of the restored soil was very low at the beginning of the measurements and
close to optimum for plant growth after three years of controlled management. Precompression stress remained low in the topsoil as well as in the subsoil over the entire study period. Precompression stress was correlated to a number of soil parameters, but it could not be successfully predicted by means of multiple linear regression functions from the measured input parameters. The compression index is often considered as a soil parameter that should not be affected by compaction. However, we found a strong positive correlation between initial void ratio and the compression index. As a consequence, the virgin compression lines of soil samples with differing initial void ratios did not align as would be expected if the samples had the same mechanical structure. The void ratio remained smaller for an initially dense soil at any given stress than for a less dense soil. It appears that the state of compaction of the restored soil was determined not only by the exerted stresses during wheeling operations but also by the initial packing after restoration. This suggests that the restoration technique has a decisive influence on the future development of the state of compaction.

The three-year study of the previously restored soil demonstrates that good physical soil quality can be achieved if adequate restoration techniques and subsequent management practices are applied. On the other hand, the results of the evaluation of 10 restored soils and 10 adjacent non-restored soils with the fuzzy logic expert system suggest that soil restoration is often associated with a decrease of physical soil quality for plant productivity. Restoration of these sites was done ignoring existing guidelines which require the use of proper parent material, the reconstruction of original soil layering, and the application of adequate restoration techniques. As a conclusion, the many uncontrolled small-scale soil restorations which can be seen nowadays in many places are more problematic than the large-scale restorations which are planned and supervised by soil experts.
Zusammenfassung


Das Ziel der vorliegenden Studie war es (1) eine Methode zur Beurteilung der physikalischen Bodenqualität auf rekultivierten Flächen zu entwickeln, diese Methode in Fallbeispielen anzuwenden und die Resultate mit bestehenden Bewertungsansätzen zu vergleichen, (2) einen einfachen Indikator für die Beurteilung der physikalischen Bodenqualität vorzuschlagen, einen entsprechenden Beurteilungsmassstab zu entwickeln und mit anderen Indikatoren zu vergleichen, (3) die Entwicklung von Indikatoren für die physikalische Bodenqualität und die mechanische Stabilität auf einer nach gültigen Richtlinien neu rekultivierten Fläche während dreier Jahre zu untersuchen und (4) multiple lineare Regressionsfunktionen für die Vorbelastung und den Kompressionsindex aus einfach messbaren Bodeneigenschaften abzuleiten.

In der vorliegenden Studie wurde ein fuzzy logic Expertensystem zur Beurteilung der physikalischen Bodenqualität entwickelt und auf 10 rekultivierten Böden und benachbarten Referenzböden angewendet. Auf der Mehrzahl der Böden verschlechterte sich mit der Rekultivierung die physikalische Bodenqualität oder sie blieb unverändert. Nur in zwei der untersuchten Horizonte konnte eine Verbesserung beobachtet werden.
Zusammenfassung


In einer Feldstudie auf einer frisch und gemäss Richtlinien rekultivierten Fläche wurden über drei Jahre die Entwicklung einiger Indikatoren für die physikalische Bodenqualität (Lagerungsdichte, Makroporosität und Eindringwiderstand) und für die

1

Introduction

Proper soil restoration on former construction or exploitation sites and on levelled agricultural land is of increasing importance and is a cornerstone of sustainable resource management. Environmentally sound restoration of land for agricultural use requires that unpolluted and biologically active soil material is used (Harris et al., 1996). Current restoration technology for example requires that top- and subsoil are excavated and stored separately to enable restoring according to the original layering of this material. However, paying attention to the quality of the soil material and respecting the original layering alone does not guarantee a successful restoration of soil for agricultural use. It is also crucial that an adequate physical quality of the restored soil is achieved and maintained during subsequent management. At the beginning of the process after excavation and refilling, most restored soils are poorly aggregated and mechanically labile. Over several years they regain strength through the development of structure (Tenholtern et al., 1996). Inadequate restoration procedures and agricultural over-use of restored soils often lead to over-compaction, water-logging and insufficient aeration, which are difficult to remediate.

Within the period from 1985 – 1997, a total area of 3167 ha of agricultural land has been restored on former landfills, construction sites and gravel exploitation sites in Switzerland (BFS, 2005). This figure corresponds to 0.2% of the total area of agricultural land, but it does not include the numerous small scale restorations following the levelling of agricultural land. Given the rapidly expanding area of restored soil and the persisting problems with the soil physical quality of these “anthropogenic soils”, soil restoration has become an important issue in soil protection.

The physical quality of a restored soil largely depends on how the soil was treated before it was put into place at the restoration site, on the way how the soil has been refilled and repacked and on the subsequent management of the regenerating soil. Suitable techniques of soil restoration and appropriate ways of soil treatment on construction sites have been proposed in several official guidelines (VSS, 2000;
BUWAL, 2001; FSK, 2001). These Swiss soil restoration guidelines assume that if tillage and heavy traffic is avoided, restored soils regain sufficient stability within three years to allow normal agricultural land management. However, little is known about the process of structure regeneration and the development of physical and mechanical properties of restored soils. At present, there is a lack of methods suited for practical applications to monitor and assess the physical quality of restored soils for plant production and their sensitivity to compaction (Friedli et al., 1998).

Recently, the awareness of the importance of soil and land evaluation has increased in the context of sustainable land use and management and led to the introduction of "soil quality" as a basic concept (Larson and Pierce, 1994). Soil quality has been defined by Karlen et al. (1997) as "the capacity (or fitness) of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, to maintain or enhance water and air quality, and to support human health and habitation". Hence, the concept of soil quality represents a holistic view of soil and its functions within the ecosystem. It is emphasizing that soils always perform several functions simultaneously and that any evaluation of the quality of a given soil must consider its multifunctional role. However, despite many proposals, no consistent procedure exists how to implement the soil quality concept in practice. In fact, the application of the soil quality concept faces many problems. It is in many cases not well understood how specific soil parameters can be interpreted as indicators of a soil function and how a specific soil function contributes to soil quality. The soil quality concept has also been criticized for not taking into account that different soil functions may be in conflict with each other (Sojka and Upchurch, 1999).

The most obvious function of soil that has been restored for agricultural land use is to provide a suitable medium for plant growth. Restored soil has to reach the twin objectives (1) of providing favorable conditions for crop production and (2) of having sufficient bearing capacity to sustain the agricultural management operations which are necessary for its cultivation. The evaluation of soil restoration has to take both objectives into account and should be based on parameters indicating the suitability of a
restored soil for crop growth as well as on parameters characterizing its mechanical stability against compaction.

The first objective refers to an evaluation of the physical quality of soil for plant production. A variety of soil parameters has been proposed as indicators for the physical quality of a soil, including soil texture, bulk density, coarse porosity, plant-available water capacity, hydraulic conductivity and penetration resistance (Larson and Pierce, 1994; Doran and Parkin, 1996). Most of these indicators are interdependent, and it is not straightforward to set individual threshold values for them. Whether plant growth is adversely affected by a specific soil parameter may also depend on the other parameters. In addition, the ranges of bulk density, coarse porosity and penetration resistance values allowing for sufficient soil aeration and unrestricted root growth will differ with soil water regime (Letey, 1985). The relationship between many soil physical parameters and plant growth is empirically evident, but depend on specific conditions and are not necessarily transferable from one soil to another. The evaluation of physical soil quality for plant production has to address the interdependence of the various parameters, as well as the ambiguity and vagueness in our understanding of the functional relationships between indicators and plant growth.

The mechanical stability of an agricultural soil against compaction by trafficking can be characterized by its precompression stress (Horn and Lebert, 1994). The concept of precompression stress assumes that deformation is fully elastic (i.e. reversible) at stresses below and plastic (i.e. irreversible) at stresses above the precompression stress (Kirby, 1991). According to this concept, stress leads to irreversible changes of physical properties only, if it exceeds the precompression stress. The ratio of stress resulting from traffic operations to precompression stress can be interpreted as a stability criterion of a soil. The precompression stress of a soil can be measured by means of compression tests or predicted from basic soil properties using pedotransfer functions (Horn and Fleige, 2003). Pedotransfer functions that have been developed for undisrupted soil may not be applicable to restored soils, though.
Addressing the need for an improved evaluation framework for restored soils, the specific objectives of this study were

- to develop a methodology for the assessment of the quality of restored soils and to compare the methodology with existing schemes of soil quality evaluation,
- to monitor the development of physical quality indicators on a soil that had been restored according to pertinent regulations
- to derive a simple indicator for the assessment of physical soil quality and to compare the critical limits of this indicator with existing soil quality indicators,
- to determine the development of the precompression stress (PS) and of the compression index (CI) of various soils during the first 3 years after restoration and to develop pedotransfer functions to derive both PS and CI from basic soil properties.

The study consists of four parts:

- Chapter 2 gives a literature review about the concept of soil quality and discusses recent approaches to evaluate soil quality.
- Chapter 3 presents a newly developed fuzzy logic expert system for the evaluation of restored sites. The expert system is based on the statements of a group of soil scientists relating the physical quality of soil for plant production to values of packing density, penetration resistance, air capacity and saturated hydraulic conductivity. From the statements of the consulted experts we derived fuzzy membership functions and inference rules to assess the physical soil quality for plant production. The expert system is applied to the evaluation of 39 soil horizons of 10 restored soils and adjacent reference soils. The validity of the fuzzy logic expert system is investigated by comparing the evaluation results with other indicators of the physical quality for plant production, such as the slope of the soil water retention curve at the inflexion point (S-parameter) and the least limiting water range (LLWR).
- In Chapter 4 we test the hypothesis that optimum and limiting values for bulk density reported in the literature are correlated to both clay and silt content. Then we convert the reported optimum bulk density and limiting bulk density values into
respective values of optimum packing density and limiting packing density and establish critical ranges for packing density values in regard to crop growth. We used a data set of 59 soil profiles from Northern Switzerland to compare the published critical limits for plant growth based on the three chosen soil compaction indicators packing density, S-parameter and least limiting water range. The packing density of the samples was calculated from the measured bulk density and clay content, whereas the values for least limiting water range and S-parameter were determined from other soil properties by means of published pedotransfer functions.

- Chapter 5 reports the analysis of a field experiment performed on a restored site, in which we monitored the regeneration of physical quality indicators (bulk density, coarse porosity, penetration resistance) of a soil which had been excavated, stock-piled, back-filled and subsequently cultivated for three years according to pertinent regulations. In addition, we monitored the development of precompression stress and compression index as indicators for the mechanical stability of the soil and developed multiple linear regression equations to calculate the precompression stress and the compression index from soil texture, bulk density and coarse porosity.

References


2 Evaluation of soil quality

2.1 Introduction

Soil quality has been defined by Karlen et al. (1997) as “the capacity (or fitness) of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation”. Soil quality encompasses two dimensions and can be viewed in two different ways: (1) as inherent properties of a soil and (2) as the condition of a soil under the influence of human use and management (Pierce and Larson, 1993). Inherent properties of a soil are determined by the factors of soil formation – climate, topography, vegetation, parent material and time. Inherent properties govern the full or ideal potential of a soil to perform a specific function – some soils are able to function at higher potentials than other soils. Soil quality as determined by inherent properties is therefore useful for comparing the potential of one soil against another in regard of a specific land use (Mausbach and Seybold, 1998). The second method for evaluating soil quality is assessing the dynamic nature of soil quality under the influence of human land use and management. It assumes, that if a soil is functioning at full potential for a specific land use, it has high quality, whereas if a soil is functioning well below its potential, it is considered to have impaired or poor quality (Karlen et al., 1997). However, there is a continuum between dynamic properties reflecting changes in soil quality and inherent properties that reflect the potential of the system to function. Therefore, the dynamic indicators should be interpreted with reference to the inherent soil properties (Herrick, 2000).

2.2 Soil functions

The concept of soil quality is based on a holistic view of soil and its functions within the ecosystem. It assumes that soils always perform several functions simultaneously and that any evaluation of the quality of a given soil must consider its multifunctional role. Nortcliff (2002) mentions the following soil functions:
• provide a physical, chemical and biological setting for living organisms
• regulate and partition water flow, storage and recycling of nutrients and other elements
• support biological activity and diversity for plant growth and animal productivity
• filter, buffer, degrade, immobilise and detoxify organic and inorganic substances
• provide mechanical support for living organisms and their structures

These functions refer to the capacity of a soil to maintain soil ecosystem health. Soil functions are sometimes also defined from a more user-oriented perspective (e.g., crop productivity, trafficability and workability, water quality, etc.). Assessing soil quality from a specific user-oriented view might be fundamentally different than evaluating soil quality from a holistic environmental perspective. Any soil quality evaluation must therefore clearly specify which functions of the soil are addressed and for what purpose it is conducted.

A soil is always part of a landscape, and its ability to perform specific functions is strongly dependent on the local climatic conditions and its position in the landscape. Pieri et al. (1995) associate the abovementioned functions rather with “land quality” than with “soil quality”. Land refers to the combined resources of soil, water, vegetation and terrain that together provide the basis for land use. The term “land” expresses the broader context in which the soil functions (Bouma, 2002).

But how can the functioning of land or of soil be characterized? And what should be the relative weight of the different, but interrelated soil functions in a soil quality evaluation system? The first question calls for selecting suitable indicators, for establishing causal relationships between the indicators and soil functions under consideration and for defining reference values for soil properties, indicating good or poor soil functioning. The second question refers to approaches to integrate the individual soil functions into a sort of soil quality index. Both questions will be addressed the next two sections.
2.3 Soil quality indicators

2.3.1 Minimum data sets

Soil quality cannot be measured directly, but must be derived by measuring changes in various soil properties or characteristics of the ecosystem. According to Doran and Parkin (1994) indicators of soil quality should (i) encompass ecosystem processes and relate to process-oriented modelling, (ii) integrate soil physical, chemical and biological properties and processes, (iii) be accessible to many users and applicable to field conditions, (iv) be sensitive to variations in management and climate, and (v) be components of existing soil databases where possible. In addition, they should be easily measurable in a reproducible manner and sensitive indicators of human induced changes (Arshad and Coen, 1992). Numerous soil properties have been suggested as indicators for soil quality. Larson and Pierce (1991) proposed a list of basic indicators of soil quality, which they termed Minimum Data Set (MDS). The MDS represents a composite of physical, chemical and biological soil properties that are related to the soil functions under consideration. In the meantime, similar MDS have been proposed also by other authors (Doran and Parkin, 1994; Gregorich et al., 1994; Larson and Pierce, 1994). In Tab. 2.1 the MDS of Mausbach and Seybold (1998) is presented that tries to summarize and integrate the previous work.

In selecting soil properties or soil indicators to describe soil functions, a number of issues have to be considered which are addressed in the following sections.

2.3.2 Understanding the causal relationship between the indicator and the function

Mathematical modelling can be used to quantify the effects of soil indicators on soil functions and to predict the rate and direction of soil quality change. For example, Lipiec et al. (2003) give an overview about soil compaction effects on crop growth and water and chemical movement in soils as predicted by empirical (or functional) and mechanistic (or process) models. A mechanistic model incorporates the most fundamental mechanisms of a process (Addiscott, 1998). Empirical models use simple mathematical equations that are purely empirical or only loosely based on physical process understanding (Connolly, 1998). They simply define the relationship between input and output variables, but they do not picture the underlying dynamic processes. In empirical models, a specific soil function (e.g. plant production) can be quantified by
regression equations that empirically describe the relationship between the soil indicator and the soil function under consideration. In functional models it is likely that weighting factors and equations will vary from region to region and from soil to soil, whereas a mechanistic model can to a certain extent be extrapolated to situations that have not been investigated for the development of the model. The main weakness of mechanistic models is that they generally require an extensive input of quantitative data. Both types of models rely on measurable soil indicators as input data to obtain a quality statement of a function as output. If the indicator is difficult to measure or not available, it might be derived by pedotransfer functions (PTF) from other soil properties that are easier to determine (Bouma, 1989). PTF relate different soil indicators or properties with one another or to soil and land qualities. PTF are often highly site and soil specific. Their use should be restricted to sites with similar physical, chemical and biological characteristics as those for which they have been validated.

Tab. 2.1: Proposed Minimum Data Set (MDS) of physical, chemical, and biological indicators for screening the condition, quality, and health of soil.

<table>
<thead>
<tr>
<th>Indicators of Soil Condition</th>
<th>Relationship to Soil Condition and Function; Rationale as a Priority Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
</tr>
<tr>
<td>Texture</td>
<td>Retention and transport of water and chemicals; modeling use, soil erosion and variability estimate</td>
</tr>
<tr>
<td>Depth of soil, topsoil, and rooting</td>
<td>Estimate of productivity potential and erosion; normalizes landscape and geographic variability</td>
</tr>
<tr>
<td>Infiltration and bulk density (BD)</td>
<td>Potential for leaching, productivity, and erosivity; BD needed to adjust analyses to volumetric basis</td>
</tr>
<tr>
<td>Water holding capacity</td>
<td>Related to water retention, transport, and erosivity; available H₂O; calculate from BD, texture, and OM</td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td></td>
</tr>
<tr>
<td>Soil organic matter (OM)</td>
<td>Defines soil fertility, stability, and erosion extent; use in process models and for site normalization</td>
</tr>
<tr>
<td>pH</td>
<td>Defines biological and chemical activity thresholds; essential to process modeling</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>Defines plant and microbial activity thresholds; presently lacking in most process models</td>
</tr>
<tr>
<td>Extractable N, P, and K</td>
<td>Plant available nutrients and potential for N loss; productivity and environmental quality indicators</td>
</tr>
<tr>
<td><strong>Biological</strong></td>
<td></td>
</tr>
<tr>
<td>Microbial biomass C and N</td>
<td>Microbial catalytic potential and repository for C and N; modeling: early warning of management effects on OM</td>
</tr>
<tr>
<td>Potentially mineralizable N</td>
<td>Soil productivity and N supplying potential; process modeling (surrogate indicator of biomass)</td>
</tr>
<tr>
<td>Soil respiration, water content, and temperature</td>
<td>Microbial activity measure (in some cases plants) process modeling; estimate of biomass activity</td>
</tr>
</tbody>
</table>
2.3.3 Spatial and temporal variability

Soil indicators often vary considerably and in complex spatial and temporal patterns within a sampling unit. This variability differs between selected soil indicators and may also be soil and site specific. In statistical terms, it constitutes a natural background “noise” from which the “signals” of impacts that these parameters are supposed to indicate must be discriminated. As many changes in soil properties are slow and occur over long periods of time, the effect of today’s management practices and other impacts may not appear for decades. Identifying significant changes of such soil indicators is only possible in long-term studies. Each soil quality assessment will therefore require a specific sampling strategy, taking into account soil heterogeneity, seasonal fluctuations, long-term trends and analytical uncertainties. Moreover, sampling strategies have to be set up according to the scale of the assessment (point, field, farm or landscape level). Warrick and Nielsen (1980) report that they required 2, 110 and 1300 samples, respectively, to achieve the same level of precision in the estimates of bulk density, percent clay and hydraulic conductivity.

2.3.4 Inter-dependence of soil indicators

Many soil indicators interact with and affect each other. Moreover, the meaning of an indicator value for a specific soil function is at the same time dependent on other indicator values. Whether, for example, a high bulk density is limiting for crop growth depends also on the absence or presence of a stable system of connected coarse pores that will allow for water infiltration, sufficient aeration and root growth. Moreover, if a soil indicator is used to describe more than one soil function it is likely that its functional interpretation will be different (Harris et al., 1996). For example, high nitrate values are good for crop production but bad for groundwater protection. A soil which is considered to be of high quality for one function may not be so for other functions.
2.3.5 Analytical (qualitative) and descriptive (quantitative) indicators

Assessments of soil quality can be done on a continuum from highly analytical to fully descriptive expressions of soil indicators. Liebig and Doran (1999) categorize the assessment approaches in 4 groups: (1) laboratory-analytical, based on well established protocols and often considered as standards to which other assessments are compared, (2) field-analytical, allowing for quantitative, on-site measurement of soil quality indicators, (3) field-descriptive, relying upon visual and tactile observations but following specific classifying methods (4) farmers’ perceptions, based on observational field experiences using organoleptic assessments, e.g. information based on our senses of sight, touch, taste and smell, and using words as descriptors. These four approaches differ in the demand for time, resources, technical expertise and in measurement accuracy. In general, the analytical approaches deliver the most accurate measurements but are often of limited availability to soil surveyors, time-consuming and costly. The descriptive approaches are generally used in soil surveys and by farmers. They require moderate or minimal resources, but their accuracy depends considerably on the experience and of personal bias of the evaluator. The contrasting strengths and weaknesses of the two approaches calls for farmer-scientist partnerships to integrate farmers’ knowledge into soil quality assessment tools used to guide management decisions (Garlynd et al., 1994; Romig et al., 1995; Wander and Drinkwater, 2000).

2.3.6 Indicators for soil resilience

Many soil quality indicators have a limited power to predict soil responses to disturbances. The capacity of a soil to continue to support the same potential range of uses in the future as it supports today depends on both its resistance to degradation and on its resilience, i.e. its potential to recover upon degradation (Herrick, 2000). In engineering sciences, resilience means tolerance against stress and is associated with the limit of elastic deformation of a body, i.e. the proportion of the total deformation which is reversed after the removal of the deforming forces (Szabolcs, 1994). If this definition is used in soil science, soil resilience is maintained as long as an applied stress does not exceed the precompression stress of a soil. However, in soil science, the concept of soil resilience is also used in a broader sense. Soil resilience encompasses all processes that enable soils to buffer physical, chemical, and biological impacts. In the soil quality
concept, resilience is linked with quality: high-quality soil has a high resilience to recover from impacts due to poor management or poor weather conditions (Bouma, 2002).

2.4 Reference systems

2.4.1 Reference systems without external quality standards

Once specific soil indicators have been identified to describe the soil functions under consideration, reference systems have to be defined for the indicators. Such reference systems can be based on specific quality standards, defined as acceptable limits or ranges. Often they are derived from expert knowledge. Less sophisticated reference systems can also be based on comparisons of indicator values among different management systems, on comparisons with average indicator values of a specific soil type or on comparisons with natural conditions of undisturbed soils. The latter reference systems avoid the setting of external and explicit quality standards and are mainly based on the monitoring of changes in the soil indicators. In the following some reference systems without external quality standards will be presented.

Comparison of values of soil quality indicators

Many studies on the effects of soil tillage and cropping practices are based on soil quality indicators without indicating specific reference values (Wander and Bollero, 1999; Islam and Weil, 2000; Liebig et al., 2004). Management systems are evaluated by comparing and statistically analysing how they influence a set of given soil quality indicators. Depending on the indicator, a “more is better” or “less is better” approach is used in the discussion of the values. If a baseline for comparison is to be established, it may be the same site at a previous time or a reference site at the same time. Other studies use factor or principal component analysis to identify which soil quality indicators best discriminate between management systems, but give no reference about the desirable range of the soil indicator values (Schipper and Sparling, 2000; Shukla et al., 2006).

Relating disturbed soil to soils under natural conditions

Another approach is to compare soils that have been cultivated under certain land management practices with similar soils that have not been disturbed. The influence of
climate and geomorphology can be eliminated if only soils within the same ecological region or soil type are compared. Comparing cropped soil to virgin soil will allow for the delineation of the nature and extent of the changes in soil quality due to cropping. Virgin soil will also give an indication of the level of soil quality that is maintained through natural processes (Reynolds et al., 2002).

*Relating actual performance of a function to the average performance of a function*

Gomez et al. (1996) designated trigger or threshold levels to evaluate the sustainability of soil management at the farm level. The framework both accounts for the interests of the farmer and concerns for soil and water resources. The threshold values for sustainability were identified for crop yield, profit, risk of crop failure, soil depth, percent soil cover and soil organic matter content relative to the local average conditions (e.g. if yield is 20% better than the regional average, the farm system is considered to be sustainable).

### 2.4.2 Value-based reference systems

With the approaches presented above, soil quality can only be evaluated in relative terms, as no external reference values are given, and no method for an aggregation of the indicators is provided. However, defining quality standards for soil indicators is the focal point of the soil quality concept. Critical (threshold, trigger, baseline, or reference) limits in soil quality assessment refer to a specific value or range of a soil indicator below (or above) which a soil process or function is impaired or adversely affected (Carter, 2002). Identifying how individual soil quality indicators can be translated into quality scores for a soil function is the major challenge for current and future soil quality research. While this point is often emphasized in the literature about the soil quality concept, only limited efforts have been made to determine such ranges, limits or reference values for specific indicators. There is consensus that the definition of a value-based reference system has to be site and soil specific. It will further depend on the land use and on the focus and purpose of the soil quality assessment. As a consequence, a value-based reference system will not be directly transferable from one application to another. If a value-based reference system is to be developed for a site and soil specific research or management question there are major challenges:
• A critical limit of a soil indicator can depend on the limits of other soil properties and the interactions among soil quality indicators (Arshad and Martin, 2002).
• The causal relationships between soil properties and soil functions are reasonably well established only for those functions that are directly related to crop production and soil erosion (Herrick, 2000), but to a lesser extent for other soil functions.

Despite the mentioned limitations and challenges, several methods and approaches have been developed to define value-based reference systems for soil quality indicators. Such value-based reference systems are based on the values for indicators which define a condition representative of a soil functioning at full potential (Mausbach and Seybold, 1998). Full potential refers to the maximum capacity of a soil to function under a particular use. Among the variety of approaches that have been developed to define full potential and corresponding critical ranges or limits for soil indicators, the following are the ones that receive the most attention in the soil quality literature.

_Relating the actual performance of a function to the full potential of a function_

If crop growth is considered as soil function, the highest potential yield can be calculated by simulation models as a means to characterize agricultural production of a given type of soil under a given climate. The ratio of actual yield (measured or calculated using simulation models) to potential yield is then defined as land quality (Bouma, 2002). Bouma et al. (1998) used the land quality concept to assess the potential impact of soil degradation (erosion and compaction) and soil amelioration (liming) in tropical soils. The model uses estimated infiltration rates, depth of rooting and available water as input variables. The actual yield is predicted by the model taking account of limited water supply, erosion, compaction and liming. The calculated actual yield is then compared to the highest potential yield under optimal conditions. The impact of soil degradation and soil amelioration is considered by its influence on the input variables.
Productivity index determined by sufficiency levels for selected indicators

Pierce et al. (1983) defined a productivity index (PI) based on the requirements to obtain sufficient root growth for the indicators bulk density, available water capacity and pH. The authors postulated levels of sufficiency \( (L_{\text{Suf}}) \) as non-dimensional parameters that can take values between 0 and 1. A sufficiency function for each indicator is relating an indicator value to a level of sufficiency. For example, the sufficiency function for bulk density was derived by defining non-limiting \( (L_{\text{Suf}} = 1) \), critical \( (L_{\text{Suf}} = 0.86) \) and root limiting \( (L_{\text{Suf}} = 0) \) bulk densities for different texture classes based on published data. The PI of a soil horizon was then calculated by the product of the sufficiencies of the three indicators and a horizon-specific weighting factor. The overall PI is the sum over the PI of the various soil horizons.

Soil quality index

Doran and Parkin (1994) proposed a soil quality index to provide an evaluation of the major soil ecosystem functions. The index consists of six quality elements which are combined simply by multiplication:

\[
\text{SQ} = (k_1E_1)(k_2E_2)(k_3E_3)(k_4E_4)(k_5E_5)(k_6E_6) \tag{2.1}
\]

where \( k_1 - k_6 \) are weighting factors, and \( E_1 - E_6 \) are soil quality elements (\( E_1 \) is food and fibre production, \( E_2 \) is erosivity, \( E_3 \) is groundwater quality, \( E_4 \) is surface water quality, \( E_5 \) is air quality and \( E_6 \) is food quality).

The authors then proposed to evaluate each soil quality element in relation to five specific soil functions: \( (F_1) \) ability to hold, accept and release water to plants, streams and subsoil, \( (F_2) \) ability to hold, accept and release nutrients and other chemicals, \( (F_3) \) promote and sustain root growth, \( (F_4) \) maintain suitable habitats for soil organisms and \( (F_5) \) respond to management and resist degradation. Mathematical relationships must be established to relate the soil functions to each soil quality element. In a last step, each soil function is expressed in terms of a minimum data set of measurable soil indicators. For each soil quality element the mathematical expression for a given soil function may take a different form.
Standard scoring functions

In a systems engineering approach, Karlen and Stott (1994) related soil indicators to soil functions by means of standard scoring functions that convert a specific soil indicator value into a standardized score ranging from 0 to 1 (see Fig. 2.1). Three types of standard scoring functions can be selected: a) more is better, b) optimum, c) less is better. The shape of the functions is established by setting lower and upper threshold and baseline values for each soil indicator. These are generally based on literature values or on expert opinion (Karlen et al., 1994a; Karlen et al., 1994b). It is of critical importance to clearly document the reasons why some particular value was chosen as a threshold or baseline value (Harris et al., 1996). In case different indicators are to be combined into an overall soil quality index, their individual scores can be multiplied by weighting factors and then aggregated by addition. This approach was applied in soil quality evaluation of three long-term tillage systems by Hussain et al., (1999). Soil quality was expressed in terms of the performance of the three soil functions (1) resist erosion, (2) provide plant nutrients and (3) provide a favourable root environment.

![Fig. 2.1: Types of standard scoring functions (SSF) used for transformation of soil quality indicators. a) more is better, b) optimum and c) less is better. Abbreviations: L: lower threshold; B: baseline, at which score is 0.5 and which is generally regarded as minimum target value; U: upper threshold; O: optimum level. Source: Hussain et al. (1999).](image-url)
Fuzzy sets

A fuzzy set is a set without sharp boundaries. It is characterized by a fuzzy membership degree that ranges from 0 to 1, indicating a continuous increase from non-membership to complete membership. Similar to the above mentioned scoring functions, a soil indicator value is associated with a specific degree of membership (see Fig. 2.2). Fuzzy sets of different soil indicators can be combined in a composite fuzzy membership model simply by weighted summation of the individual membership degrees to build a fuzzy soil quality index (Tobias and Tietje, 2007). Moreover, fuzzy sets can be combined in fuzzy logic expert systems to simulate human reasoning by using heuristic rules provided by human experts (McBratney and Odeh, 1997). Fuzzy logic expert systems are a tool for modelling and understanding decision rules in criteria evaluation and combination. They allow for including the interactions among soil indicators in the assessment of soil functions. An example of a fuzzy logic expert system for evaluating the potential plant productivity of restored soils is presented in Chapter 3.

![Fig. 2.2: Fuzzy sets for the soil indicators “packing density” and “penetration resistance”, expressed in the linguistic terms “optimal for crop growth” (full line), “inhibiting for crop growth” (dashed line) and “limiting for crop growth” (dotted line). A specific soil indicator value may belong at the same time to all three fuzzy sets, but to a different degree of membership (e.g. a penetration resistance value of 4 MPa belongs with a membership degree (MD) of 0.3 to the set “optimal for crop growth”, with a MD of 0.6 to “inhibiting for crop growth” and with a MD of 0 to “limiting for crop growth”.)](image-url)
Threshold values indicating good soil quality

Smith et al. (1993) presented an approach to integrate an unlimited number of soil quality indicators to an overall assessment of soil quality. In this approach, critical thresholds are determined by the users in the form of minimum acceptable values, maximum allowable values or acceptable values within a specific range. Before a soil is judged to be of good quality, the user has to define how many indicators must meet their respective critical thresholds or ranges. If, for example, the number of indicators is five, it might be requested that three of the criteria must be met without defining which specific soil indicators must be within the acceptable range. Alternatively, it could be required that a certain crucial indicator must be met, as well as a minimum proportion of the other indicators. This allows for weighting some indicators more than others.

Control charts

Pierce and Larson (1993) suggested to use control charts for monitoring soil quality over time. Control charts are applied in statistical quality control in the manufactured goods industry. A control chart uses a quality standard and upper and lower control limits that are based on natural variation for each soil indicator. As long as an indicator value is within the control limits, representing the desired level of soil quality, the process or system is considered to be under control. Values outside the control limits indicate a change in soil quality. Da Silva and Kay (2004) successfully used control charts for relating the difference of the actual water content to either the upper or lower specification limit of the least limiting water range with plant growth.

2.4.3 Value-based reference systems for the assessment of soil compaction

The following chapters are mainly concerned with the physical quality of restored soils, where compaction with adverse effects for plant growth is the major issue. Therefore, a specific focus is given in the following sections to a number of value-based reference systems that were developed for the assessment of physical soil quality and the state of compaction of agricultural soil.
Chapter 2

Packing density

Renger (1970) defined packing density of a soil as a composite index of bulk density and clay content according to the formula:

\[
PD = BD + 0.009 \ C
\]  
(2.2)

where PD is packing density (\(-\)), BD is bulk density (g cm\(^{-3}\)), and C is clay content (weight-%)

At constant bulk density, packing density increases with increasing clay content. This accounts for the fact that a clayey soil of a given bulk density is more “compact” than a sandy soil with the same bulk density. Thus, packing density allows to compare the state of compaction of soils with different textures. Renger (1970) and Harrach (1999) classified packing density with respect to the state of soil compaction.

Least limiting water range

Da Silva et al. (1994) introduced the concept of the least limiting water range (LLWR) as an index of the structural quality of a soil for crop growth. The LLWR is the range in soil water content within which limitations to plant growth associated with water potential, aeration and mechanical resistance are minimal. The range of water content that is optimal for plant growth is generally assessed in terms of water storage between field capacity and the permanent wilting point. In the concept of the LLWR, this range can further be reduced by a high penetration resistance on the dry side and by poor aeration on the wet side. Therefore, the LLWR of a soil can be directly linked to physiological processes that have a strong influence on plant growth (Kay et al., 2006). The LLWR becomes narrower if bulk density increases (see Fig. 4.4). If the LLWR is narrow, the likelihood is high that the soil water content falls outside the LLWR throughout the growing season, with adverse effects for plant growth. The bulk density at which the LLWR reaches zero has been termed critical bulk density (Leao et al., 2006).
The slope of the water retention curve at the inflection point

Dexter (2004a) introduced a soil quality indicator based on the slope of the soil water retention curve, the so called S-parameter. S is the modulus of the slope of the soil logarithmic water retention curve at its inflection point (see Fig. 4.3). The S-parameter is an indicator of the amount of structural porosity (i.e. cracks, bio-pores and macrostructures). Structural porosity is important for root growth and is very sensitive to soil compaction. Dexter (2004a, 2004b, 2004c) showed that the S-parameter is positively correlated to root growth, soil friability and unsaturated hydraulic conductivity (at the water potential corresponding to the inflexion point) and developed categories for the S-parameter as an index of soil physical quality.

Degree of compactness

Håkansson (1990) introduced the degree of compactness (D) as a physical indicator for crop yield. D is defined as the dry bulk density of a soil in percent of a reference bulk density obtained by a standardized uniaxial compression test on large samples at a stress of 200 kPa. On annually tilled mineral soils of the plough layer, maximum crop yield was obtained at the same D-value irrespective of the soil type. As this optimal D-value is virtually independent of soil texture, it is generally applicable for the description of the state of compactness of a soil with respect to compaction effects on crop yields. In contrast, bulk density or porosity values indicating optimal conditions for crop growth vary greatly between soils of different texture. Optimal D-values indicate potential for maximal crop yields. Various authors have determined such values (Riley, 1988; Lipiec et al., 2000).

2.5 Discussion

The soil quality concept has met with fundamental criticism (Sojka and Upchurch, 1999; Singer and Ewing, 2000; Sojka et al., 2003). It focuses on the following potential pitfalls: (1) Soil functions occur simultaneously, but are sometimes antagonistic. No convincing approach has been presented that allows for taking conflicting soil functions into account. (2) Soil quality as defined in the concept cannot be derived strictly from scientific principles, but involves subjective value judgements. A mixture of scientific and non-scientific judgements is applied to score soil quality and to weigh soil
functions. Moreover, there is no clear distinction between scientific-based and value-based judgements. (3) Although the soil quality concept follows a holistic approach in theory, the quality evaluations that are carried out in practice focus mainly on crop productivity or crop yield. Thus, soil quality has basically become a substitute term of soil productivity. (4) The introduction of soil quality as an aggregated index is of little use for decision makers and to guide management. As more information is combined in the evaluation process, concrete conclusions become harder to derive. The aggregated score must be de-aggregated again in order to understand the functional relationships that are necessary to arrive at meaningful interpretations and to make proper soil management decisions.

In conclusion, the critics suggest to put the emphasis rather on quality soil management than on soil quality management. Understanding rather than rating the soil resource should be the primary goal of soil science. Wander and Drinkwater (2000) state that, although the soil quality concept is relatively well established and increasingly accepted, it remains difficult to see how the complex and site-specific nature of soils can be translated into measurable parameters adequately reflecting the state of a soil. However, other authors are less pessimistic about the value and the application of the soil quality concept. According to Carter (2002), the soil quality concept is useful when it is directed or focused towards the manipulation, engineering and management of the soil resource. Karlen (2004) points into the same direction when he suggests the development, improvement and use of the soil quality concept as a basis to quantify the sustainability of various soil and crop management practices.

2.6 Conclusions

The soil quality concept is considered as a useful theoretical paradigm to take the multi-functionality of soil into account. However, the practical implementation of the concept is hindered by the constraints outlined above. Given the conceptual vagueness of the soil quality concept, it seems arbitrary to associate soil indicators with exact utility values as proposed in some value-based reference systems. Instead, the fuzzy logic approach is able to express the inherent uncertainties of the soil quality concept, to map them over the whole evaluation process from the input to the output and to visualize them as fuzzy sets. Thus, the soil quality concept can benefit from the use of
fuzzy logic expert systems. Therefore, a fuzzy logic expert system was developed in the framework of this PhD thesis to evaluate the quality of restored soils (see Chapter 3). The expert system focuses on the physical soil quality for plant production. Taking only one soil function into account, it avoids the assessment of the difficult trade-offs between potentially conflicting soil functions. On the other hand, the focus on physical soil quality for plant production allows for a comparison of the newly developed expert system with existing approaches for physical soil quality assessment.

2.7 References


3

Quality evaluation of restored soils with a fuzzy logic expert system

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Abstract

Due to landscaping, mining and construction activities on previously cultivated land, more and more soils are excavated, translocated, deposited and restored. In many cases restored soils show signs of structural degradation such as overcompaction and water logging. There is a lack of methods to evaluate and assess the physical quality of restored soil. In this study a fuzzy logic expert system was developed which allows to evaluate the potential plant productivity of restored soils based on measured physical soil parameters. The system is based on the statements of a group of soil experts relating physical soil quality to packing density, penetration resistance, air capacity and saturated hydraulic conductivity according to their personal experience or expertise. From these statements we derived fuzzy membership functions and inference rules. The expert system was applied to evaluate 10 restored sites in comparison to nearby non-restored reference soils. The physical soil quality had remained unchanged or decreased after restoration at most investigated sites. Only two horizons showed clearly improved soil conditions after restoration. The validity of the fuzzy logic expert system is demonstrated by comparing the results with evaluations of the same soils using two other indicators of the physical soil quality for plant production: the least limiting water range (LLWR) and the S-parameter (i.e. the slope of the water retention curve at the inflection point). The physical soil quality assessment with the fuzzy logic expert system was highly correlated with both the LLWR ($r^2 = 0.80$) and the S-parameter ($r^2 = 0.70$). These results show that fuzzy logic expert systems may provide a suitable tool to assess physical soil quality, taking proper account of the vagueness and ambiguity necessarily involved in this task.

Keywords
Fuzzy logic expert system; fuzzy inference system; soil quality; soil restoration; soil physical indicators; least limiting water range; S-theory.
3.1 Introduction

Soil restoration on former construction, gravel exploitation and open-cast mining sites and after leveling of agricultural land is of increasing importance and is a cornerstone of sustainable resource management. Environmentally sound restoration of land for agricultural use requires that unpolluted and biologically active soil material is used (Harris et al., 1996). Current state-of-the-art restoration technology includes the separate excavation and storing of top- and subsoil material to enable restoring according to the original layering of this material (Häusler and Salm, 2001). However, paying attention to the quality of the soil material and respecting the original layering alone does not guarantee a successful restoration of soil for agricultural use (Barnhisel, 1988). It is also crucial that the packing and subsequent management of the soil lead to adequate physical quality (Beaudet-Vidal et al., 1998). Inadequate restoration procedures and over-use of freshly restored soils often leads to over-compaction, water-logging and insufficient aeration, which are difficult to remediate. In order to improve the success of soil restoration, it is necessary to monitor the development of the structure-related physical properties of restored soils. Several indicators are available to assess the physical quality of soils (da Silva and Kay, 1997; Lipiec and Håkansson, 2000; Dexter, 2004a). But there is a lack of an integrated method to assess and evaluate the physical quality of restored soils based on a set of several easily measurable parameters (Friedli et al., 1998).

Recently, the awareness that soil and land evaluation are an important basis for sustainable land use and management has increased and led to the introduction of "soil quality" as a basic concept of soil monitoring (Larson and Pierce, 1994). According to this concept, soil simultaneously performs a multitude of different functions and all these functions contribute to soil quality. Karlen and Andrews (2000) defined soil quality as “the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation”. Numerous soil parameters have been suggested as indicators for soil quality. Doran and Parkin (1996) proposed a list of basic indicators of soil quality, which they termed *minimum data set* (MDS). The MDS comprises a variety of physical, chemical and biological soil
parameters that are related to the different soil functions. Soil quality is evaluated on the basis of these indicators in terms of the capacity of a soil to perform soil functions.

At present, despite many proposals, no consistent procedure exists how to implement the abovementioned, holistic soil quality concept in practice. The application of the concept is faced with several problems. For many soil conditions it is not well understood how specific soil parameters can be interpreted as indicators of a soil function and how a specific soil function contributes to soil quality. The soil quality concept has also been criticized for not taking into account that different soil functions may be in conflict with each other (Sojka and Upchurch, 1999). It has been proposed to relate soil indicators to soil functions by means of standard scoring functions that convert a specific soil indicator value into a utility score (Karlen and Stott, 1994), see Fig. 3.1. However, this approach makes it difficult to account for interactions between different soil indicators. In addition, it implies that the utility scores of soil indicators can be accurately specified and quantified for soil functions. But given the immanent conceptual vagueness of the soil quality concept, it seems arbitrary to associate soil indicators with exact utility values. Moreover, as the significance of a soil indicator for a soil function may considerably vary with climate, soil type, crop, management, etc., a multitude of scoring functions would have to be defined to account for all the factor combinations.

![Figure 3.1: Framework of soil quality assessment (Karlen and Stott, 1994).](image-url)
In this paper we develop an approach to evaluate the physical quality of restored soils by means of a fuzzy logic expert system. Fuzzy logic was introduced by Zadeh (1965) as a tool to describe and analyze ambiguity, vagueness and ambivalence in conceptual or mathematical models of empirical phenomena (Kandel, 1986). Since the 1980s fuzzy logic has been used in soil science for soil evaluation and classification (Burrough, 1989). Fuzzy logic expert systems have been developed to simulate soil-based reasoning processes, for example to predict crop yield (Ambuel et al., 1994), to model farmers’ knowledge for land suitability classification (Sicat et al., 2005), to determine the state of and the susceptibility to compaction (Tobias and Tietje, 2007) or to analyse degraded terrain (Genske and Heinrich, 2008). The fuzzy-set approach offers a variety of techniques enabling the agglomeration of a set of crucial soil parameters into a single index of soil quality (McBratney and Odeh, 1997).

The objective of this investigation is the development of a fuzzy logic expert system for quality evaluation of restored soils for agricultural use, hence we focus on the soil function "plant production". Soil translocation, deposition and restoration primarily affect and alter the physical structure of a soil. Thus, we base our assessment on physical soil parameters. As a consequence, the result of our evaluation is not a total soil quality index, but an assessment of the “physical soil quality for plant production”. There are already established approaches to assess the physical soil quality for plant production. We will compare the results obtained by the fuzzy logic expert system with two alternative approaches:

- Dexter (2004a) introduced a soil quality indicator, the so called S-parameter. S is the slope of the logarithmic soil water retention curve at its inflection point. The S-parameter is an indicator of the amount of structural porosity (i.e. cracks, bio-pores and macrostructures). Structural porosity is important for root growth and is very sensitive to soil compaction. Dexter (2004a,b,c) showed that the S-parameter is positively correlated to root growth and suggests to use it as an index of soil physical quality.

- Da Silva et al. (1994) introduced the concept of the “least limiting water range” (LLWR). The LLWR is the range in soil water content, within which there are minimal limitations to plant growth with respect to water availability, aeration and mechanical resistance. If the LLWR of a soil is narrow, the likelihood is high that
the soil water content falls outside the LLWR during the growing season with adverse effects for plant growth. Da Silva and Kay (1997, 2004) proposed to use the LLWR as an indicator to characterize the physical quality of a soil for crop production.

The fuzzy logic expert system developed here is based on the statements of a group of soil experts relating physical soil quality for plant production to soil packing density, penetration resistance, air capacity and saturated hydraulic conductivity on the basis of their expertise. From these statements we derived fuzzy membership functions and inference rules to assess the physical soil quality for plant productivity. The expert system is applied to the evaluation of 39 soil horizons of 10 restored sites and adjacent reference soils. The quality assessments obtained with the fuzzy logic expert system are both expressed as fuzzy sets and as defuzzified, crisp output values. The validity of the fuzzy logic expert system is investigated by comparing the resulting evaluation with an assessment obtained by using alternatively the LLWR and the S-parameter as indicators of soil physical quality for plant production.

3.2 Theory

In this section we give a brief introduction into the theory of fuzzy sets, fuzzy set operations and fuzzy logic, as far as it is needed for the understanding of the presented fuzzy logic expert system. For further information on fuzzy logic and its applications to expert systems we refer to Kandel (1986), Kaufmann and Gupta (1988), Bardossy and Duckstein (1995) and Tanaka (1997).

3.2.1 Fuzzy sets and fuzzy set operations

Fuzzy sets

The concept of fuzzy sets can be best explained by a comparison to classical sets. In classical set theory, an element is either fully included in or fully excluded from a set. In contrast, a fuzzy set has no crisp boundary. Its elements may have only a partial degree of membership. A fuzzy set is defined by ordered pairs of objects and their membership grade. Mathematically, a fuzzy subset $A$ in $X$ is the set of ordered pairs

$$A = \{ x, \mu_A(x) \} \quad x \in X$$  \hspace{1cm} (3.1)
where \( X = \{x\} \) is a set of points and \( \mu_A(x) \) is the grade of membership of element \( x \) in \( A \).

The relation \( \mu_A(x) \), also termed “membership function”, can take values in the interval \([0,1]\). \( \mu_A(x) = 0 \) means that \( x \) does not belong to the subset \( A \), \( \mu_A(x) = 1 \) means that \( x \) fully belongs to the subset \( A \), and \( 0 < \mu_A(x) < 1 \) means that \( x \) belongs to a partial degree to the subset \( A \).

If a fuzzy set is of a trapezoid shape as in Fig. 3.2a, its membership function is defined by its edge points \( a, b, c \) and \( d \). A fuzzy set is called a fuzzy singleton if it has a membership degree of 1 in exactly one point and 0 in all the other points. A fuzzy singleton can be considered as a fuzzy number without vagoneness (see Fig. 3.2b).

**Operations with fuzzy sets**

Operations with fuzzy sets are defined via their membership functions. The two most basic operations are intersection and union. The most general extension of these operations from crisp to fuzzy sets is given in the following definitions based on the \( \min \) and \( \max \) operators.

We consider two fuzzy sets \( A \) and \( B \), each belonging to a set \( X \) of real numbers \( x \in X \). The **intersection** of \( A \) and \( B \), i.e. the set \( A \cap B \), is the largest fuzzy set contained in both \( A \) and \( B \). It is given by the membership function:
\[ \mu_{A \cap B}(x) = \min(\mu_A(x), \mu_B(x)) \]  
\[ (3.2) \]

where \( \min(\mu_A(x), \mu_B(x)) \) is the minimum of the membership degrees of element \( x \) in the two sets \( A \) and \( B \). Compared with the Boolean logic of crisp sets, the fuzzy intersection (\( \min \) operator) corresponds to the logical AND (see Fig. 3.3a).

The union of \( A \) and \( B \), i.e. the set \( A \cup B \), is the smallest fuzzy set that contains all elements held in \( A \) and \( B \). It is given by the membership function:

\[ \mu_{A \cup B}(x) = \max(\mu_A(x), \mu_B(x)) \]  
\[ (3.3) \]

where \( \max(\mu_A(x), \mu_B(x)) \) is the maximum of the membership functions of element \( x \) in the sets \( A \) and \( B \). Compared with the Boolean logic of crisp sets, the fuzzy union (\( \max \) operator) corresponds to the logical OR (see Fig. 3.3b).

![Fig. 3.3a, 3.3b: Fuzzy intersection (3.3a) and fuzzy union (3.3b) of fuzzy Sets A and B with corresponding membership functions \( \mu(A) \) and \( \mu(B) \).](image)

**Fuzzy logic and linguistic variables**

In fuzzy logic, the truth of a statement is also considered to be a matter of degree, whereas in Boolean logic a statement can only be true or false. Fuzzy logic can be viewed as a generalization of the binary (TRUE or FALSE) Boolean logic, offering tools to operate with vaguely defined parameters or concepts. It can be used in particular to handle variables whose values are defined in linguistic terms and, by
means of fuzzy inference rules (IF-THEN rules), to map human reasoning processes in a formal way. Formally, a linguistic variable consists of the following elements:

- the name of the linguistic variable, e.g. "penetration resistance"
- linguistic terms, e.g. "optimal", "inhibiting", "limiting"
- a physical universe of elements on which the different linguistic terms are defined e.g. interval of penetration resistance from 0 to 10 MPa
- membership functions for the linguistic terms e.g. the membership functions for the terms "optimal", "inhibiting" and "limiting".

**Fuzzy logic expert systems**

Fuzzy logic expert systems (also termed “fuzzy inference systems”) have been introduced by Mamdani and Assilian (1975) for the control of technical systems. Fuzzy inference is the process of mapping the relationship between the input into a system to the output of the system using fuzzy logic. Fuzzy logic expert systems simulate human reasoning by applying a set of heuristic rules given by a human expert (Chak and Feng, 1998). A fuzzy logic expert system is composed of the following components: fuzzification interface, rule base, inference system and defuzzification interface (see Fig. 3.4). The fuzzification interface assigns measured input values a certain degree of membership to each of the linguistic terms of a linguistic variable. The rule base and the inference system map combinations of linguistic terms of the input variables to the output variable. The defuzzification interface transforms the fuzzy output set into a crisp score.

![Diagram of a fuzzy logic expert system](image)

*Fig. 3.4: Concept of a fuzzy logic expert system.*
3.3 Material and Methods

3.3.1 Type of expert system

For the physical soil quality expert system we used a zero-order Takagi-Sugeno-Kang model (Takagi and Sugeno, 1985). This fuzzy inference system uses inference rules such as:

IF A is v AND B is w AND C is x AND D is y THEN E is z

where A, B, C, D and E are linguistic variables, v, w, x, y and are linguistic terms, expressed as fuzzy sets, and z is a linguistic term expressed as a fuzzy singleton.

The terms following the IF statements of the rule are called the premises, the THEN-part of the rule is called the conclusion. The fuzzy AND operator (or min operator) is applied to combine the premise variables. It selects the minimum degree of membership of the input variables. The resulting degree of membership of the logically combined premises is called the adaptability of the premise part to the conclusion of the rule. The conclusion part of each rule is a fuzzy singleton, expressed as a word that is associated with a distinct numerical value. The influence of the premise on the conclusion is given by the implication function. Here we use the most common implication function, which is the minimum function that truncates the output fuzzy singleton at the membership degree (or the adaptability) of the premise. In other words, if the premise is true to a certain degree of membership, then the conclusion is also true to the same degree. If the expert system consists of several rules, they are all applied in parallel. The fuzzy OR operator (or max operator) is used to combine and aggregate the output sets of the rules by fuzzy union. The aggregated output is again a linguistic variable that consists of the individual fuzzy singletons. The mechanisms of the combination of linguistic terms in a rule, the implication to the output set and the aggregation of rules are illustrated in Fig. 3.5.
Fig. 3.5: Mechanisms of a zero-order fuzzy inference system with a constant conclusion part. For simplicity, the example shows a two-premises system, whereas in our soil quality expert system four premises are used. The inputs to the system are measured values of packing density (PD) and penetration resistance (PR), the output set is the physical soil quality.

If the desired output is not a fuzzy set, but a single value, the output fuzzy set must be defuzzified. For our system we chose the centroid method for defuzzification, which determines the center of gravity of the output fuzzy set, given by

\[ C = \frac{\sum w^i z^i}{\sum w^i} \quad i = 1, 2, \ldots, r \]  

(3.4)
where $C$ is the center of gravity, $r$ is the total number of rules, $w_i$ is the adaptability of the premise part of rule $i$ and $z_i$ is the numerical value of the fuzzy singleton of rule $i$.

In our system the inputs are the measured values of physical soil parameters, which determine the degree of membership or truth of the corresponding statements in the premises of the set of rules. The logical aggregation of the individual parts of the premises determines the adaptability or degree of truth of the entire premises, which in turn determines the degree of truth of the conclusions by way of the implication function. The set of conclusions is then aggregated to an output consisting of a set of fuzzy singletons. The defuzzified output consists of one numerical value indicating the physical soil quality.

### 3.3.2 Derivation of membership functions and inference rules

As mentioned before, the fuzzy logic expert system developed here is based on the statements of a group of 20 soil experts. The group consisted of 20 members of the Swiss Soil Science Society (SSSS) working in the field of physical soil assessment and protection. The participants included researchers, field survey staff members and soil protection authority officials. They were asked to relate physical soil quality to the physical parameters packing density, penetration resistance, air capacity and saturated hydraulic conductivity. Participants were asked by means of a questionnaire to express fuzzy linguistic variables for each of the input parameters with the linguistic terms “optimal for crop growth”, “inhibiting for crop growth” and “limiting for crop growth”. The participants were provided with the necessary basic information about fuzzy sets and fuzzy expert systems. Most of them were not familiar with fuzzy logic prior to this exercise. No extra information about the physical soil parameters under consideration was given in the questionnaire. In a first step, the participants were asked to define membership functions of the fuzzy sets according to their own perception, based on their personal knowledge and experience. The fuzzy sets had to be expressed graphically. Most of the experts used trapezoidal shapes to draw the fuzzy sets. If sigmoidal or Gaussian shapes of membership functions were used, we transformed them into trapezoidal membership functions by drawing a tangent line through the inflection
point for both the increasing and the decreasing part of the membership function. Each trapezoidal function was parameterised by its edge points. To summarise the results, we determined the median value of all the individual values for a given edge point of each membership function. These averaged membership functions were then used in the expert system.

In a next step, the participants were asked to define inference rules of the parameters in relation to plant production. They combined two or more input parameters and assessed their joint effect on plant productivity on the scale “bad”, “rather bad”, ”medium”, “rather good” and “good”. Most of the experts considered a certain compensation to be possible if one parameter would indicate good conditions for plant growth and another one bad conditions. Some experts supposed the resulting plant productivity always be limited by the parameter with the worst value and allowed no compensation among parameters. Hence, the reasoning processes and the concepts for combining parameters varied considerably among the experts. While it is difficult to integrate such diversity of views in a common approach, a fuzzy expert system can integrate them by using differing kinds of views in different inference rules that are all applied in parallel (see Chapter 3.4.2).

3.3.3 Field Sampling

In order to test and apply the expert system, we sampled a total of 10 restored top- and subsoils and corresponding adjacent non-restored reference soils. The restored sites were all of small size, covering areas between 1000 and 5000 m². All sites were located in the Canton of Zurich, i.e. in north-eastern Switzerland. Most of the restored soils were in sites of former depressions, where material excavated from nearby construction and gravel exploitation sites was used to level agricultural land. The sites had been restored 3 to 5 years prior to the investigation and had been used for grassland, agricultural cropland or animal husbandry since then. An adjacent non-restored reference soil was identified at each site, belonging to the same soil mapping unit as the site of the restored soil prior to its filling and restoration.

At each site a soil profile was opened and 5 cylindrical core samples were taken at depths of 0.1 -0.2 m (topsoil) and 0.4 - 0.5 m (subsoil). In the laboratory, the volumetric samples were first water-saturated and then drained to a water potential of -6 kPa by
means of a hanging water column. The air capacity of each core was calculated from the difference between the water content at saturation and the water content at -6 kPa water potential. Then the samples were oven-dried and the bulk density was determined gravimetrically (Blake and Hartge, 1986).

Soil texture was determined from bulk samples by means of the pipette method (Gee and Bauder, 1986). Soil organic carbon content was determined with the dichromate oxidation method (Nelson and Sommers, 1982). Two replicate analyses were performed per horizon.

Packing density was determined from soil bulk density and soil texture using the following equation (AG Boden, 1994):

\[
Packing\ density\ (-) = bulk\ density\ (g\ cm^{-3}) + 0.009\ clay\ (%)\ 
\]

(3.5)

At constant bulk density, the packing density increases with increasing clay content. This accounts for the fact that a clayey soil of a given bulk density is more compact than a sandy soil with the same bulk density. Thus, the packing density is an indicator that allows to compare the compaction state of soils with different textures (Renger, 1970).

The penetration resistance was measured in the field down to a depth of 0.6 m when the soils were near field capacity using a PANDA dynamic cone penetrometer (SOL SOLUTION, Riom, France). This device records the depth of penetration of a steel-shaft (2 or 4 cm² basal cross-section and 30° semiangle) and of the kinetic energy of each strike, as the shaft is hammered into the soil (Gourves, 1996). At each site 10 measurements were performed in the topsoil (0.1 - 0.2 m depth) as well as in the subsoil (0.4 - 0.5 m depth) at a time when the soil was near field capacity.

The saturated hydraulic conductivity was determined between the soil surface and 0.3 m depth in 3 replicates at each site using the auger hole method (Amoozegar and Warrick, 1986). The median of the measured values was used for both top- and subsoil assessment.

For all parameters except the saturated hydraulic conductivity, the averages of the respective replicate measurements were used for further data analysis and processing.
3.3.4 Physical soil quality evaluation using the S-parameter

S is the slope of the logarithmic soil water retention curve at its inflection point. As S is always negative, the modulus of S is used here for convenience and is called S-parameter. The S-parameter was calculated using the following equation given in Dexter (2004a):

$$S = -n(\theta_{sat} - \theta_{res})\left(\frac{2n-1}{n-1}\right)^{\frac{1}{n-2}}$$

(3.6)

where \(\theta_{sat}\) is the gravimetric water content at saturation, \(\theta_{res}\) is the residual water content and \(n\) is a shape parameter. \(\theta_{sat}\), \(\theta_{res}\) and \(n\) are van Genuchten (1980) equation parameters and were estimated from pedotransfer functions derived by Wösten et al. (1999) using measured values of soil texture, organic matter and bulk density as inputs.

3.3.5 Physical soil quality evaluation by means of the least limiting water range (LLWR)

The calculation of the LLWR requires the specification of critical limits for soil penetration resistance and air capacity in relation to crop growth. The critical limits were selected according to the membership functions for penetration resistance and air capacity that were derived from the experts’ statements. According to these membership functions, the penetration resistance (PR) was limiting at PR values > 2 MPa and at air capacity (AC) values below 10%. These limits are in good correspondence with critical limits for penetration resistance and air capacity given in the literature (da Silva and Kay, 2004; Lipiec and Håkansson, 2000; Lapen et al., 2004; Leao et al., 2006).

The soil water content at field capacity and wilting point were calculated for each soil horizon according to the water retention pedotransfer functions of da Silva and Kay (1997) from its bulk density, clay content, and organic carbon content. Similarly, the soil water content at the critical penetration resistance of 2 MPa (\(\theta_{pr}\)) was calculated by means of the soil penetration resistance pedotransfer function (da Silva and Kay, 1997). The soil water content at the critical air capacity of 10% (\(\theta_{ac}\)) was calculated from the volumetric soil water content at saturation (\(\theta_{sat}\)), as \(\theta_{ac} = \theta_{sat} - 0.1 \text{ cm}^3 \text{ cm}^{-3}\). Following the definition of da Silva and Kay (1997), the upper limit of the LLWR was set as the lower value of the soil water content at field capacity or at \(\theta_{ac}\), and the lower limit of
the LLWR was set as the higher value of the soil water content at the permanent wilting point or at $\theta_{pr}$.

3.4. Results

3.4.1 Averaged membership functions

The averaged membership functions for the linguistic input variables “packing density”, “penetration resistance”, “air capacity” and “saturated hydraulic conductivity” are shown in Fig. 3.6. All of them are represented by trapezoids extending either to the lower or to the upper boundary of the range of values on which they are defined. The interior edge points of the membership functions are given in Tab. 3.1.

Fig. 3.6: Diagrams of the membership functions for the 4 linguistic variables packing density, penetration resistance, air capacity and saturated hydraulic conductivity. Linguistic terms are “optimal for crop growth” (full line), “inhibiting for crop growth” (dashed line) and “limiting for crop growth” (dotted line).
**Tab. 3.1: Edge points of the trapezoidal membership functions.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Descriptors of membership functions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
</tr>
<tr>
<td>Packing Density (-)</td>
<td></td>
</tr>
<tr>
<td>optimal</td>
<td>-</td>
</tr>
<tr>
<td>inhibiting</td>
<td>1.5</td>
</tr>
<tr>
<td>limiting</td>
<td>1.6</td>
</tr>
<tr>
<td>Penetration Resistance (MPa)</td>
<td></td>
</tr>
<tr>
<td>optimal</td>
<td>-</td>
</tr>
<tr>
<td>inhibiting</td>
<td>2</td>
</tr>
<tr>
<td>limiting</td>
<td>5</td>
</tr>
<tr>
<td>Air capacity (Vol-%)</td>
<td></td>
</tr>
<tr>
<td>optimal</td>
<td>7</td>
</tr>
<tr>
<td>inhibiting</td>
<td>-</td>
</tr>
<tr>
<td>limiting</td>
<td>-</td>
</tr>
<tr>
<td>Sat. Hydraul. Conduct. (cm d⁻¹)</td>
<td></td>
</tr>
<tr>
<td>optimal</td>
<td>3.5</td>
</tr>
<tr>
<td>inhibiting</td>
<td>-</td>
</tr>
<tr>
<td>limiting</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3.4.2 Rule base

Each of the 4 input variables is expressed in 3 linguistic terms. Thus, a total of $3^4 = 81$ combinations of terms had to be considered in the rule base. In order to make the rule building process more transparent and stringent, we used the following heuristic concept: Plant growth can be physically inhibited or limited by a low soil aeration status and by high mechanical resistance (Letey, 1985). Low air capacity and low saturated hydraulic conductivity is related to poor aeration at high soil water content (da Silva et al., 1994). High penetration resistance and high packing density is connected with restricted rootability at low soil water content (Harrach, 1999). As the soil water content can vary considerably throughout the vegetation period under temperate climatic conditions and both high and low soil water contents can be expected, plant growth may be physically restricted by high mechanical resistance and by poor aeration alternately. Taking this into account, we considered the joint influence of penetration resistance (PR) and packing density (PD) as indicators for the mechanical resistance of the soil and the joint influence of air capacity (AC) and saturated hydraulic conductivity (SHC) as an indicator for the aeration status of the soil. This approach divides the reasoning process into two steps: Step 1 assesses soil mechanical resistance in relation to PR and PD and soil aeration status in relation to AC and SHC. Step 2 combines the assessments of mechanical resistance and aeration status into an assessment of physical soil quality.
for plant production (see Fig. 3.7). Note that soil mechanical resistance and soil aeration status are considered only as auxiliary intermediate variables, structuring the rule building process. The auxiliary intermediate variables are not visible in the output set.

**Heuristic rule building mechanism**

![Heuristic rule building mechanism diagram](image)

**Output variable**
goog rather good medium rather bad bad

**Auxiliary variables**
very high high intermediate low very low

**Input variables**
optimal inhibiting limiting

Fig. 3.7: Heuristic rule building mechanism and linguistic terms of input variables, auxiliary variables and output variables.

The resulting rule set maps each individual combination of the linguistic terms of the four input parameters to exactly one linguistic term of the output set. The output set is the linguistic variable "physical soil quality for plant production", consisting of the five linguistic terms "bad", "rather bad", "medium", "rather good" and "good", expressed as fuzzy singletons and associated with the numeric values 1 to 5. Due to overlap of the fuzzy sets of the input parameters, a given input value may belong to more than one linguistic term at the same time. This means that several combinations of linguistic terms may apply to a given set of measured input parameters. All the corresponding rules are then applied in parallel. As a result, the output set for physical soil quality for plant production usually comprises memberships in more than one of the five fuzzy singletons. The entire expert system, including the the fuzzy membership functions and the rule set, was formulated as a spreadsheet in Excel.
The joint influence of packing density and penetration resistance on soil mechanical resistance is mapped according to the Rule set 1 (see Fig. 3.8). The heuristic assumption behind this rule set is as follows: soil mechanical resistance is assessed to be "very low" if packing density and penetration resistance are both "optimal", "intermediate" if both are "inhibiting", and "very high" if both are "limiting". In the case of the combinations "optimal AND inhibiting" or "inhibiting AND limiting" a certain trade-off is assumed, i.e. the mechanical resistance is assumed to be "low" in the first case and "high" in the second. An unusual but still possible combination is that one parameter shows "optimal", the other "limiting" conditions. Allowing again for some compensation, the mechanical resistance is then considered to be intermediate. Rule set 2 (see Fig. 3.8) describes the joint effect of air capacity and saturated hydraulic conductivity on the soil aeration status. Analogous assumptions of compensations between the two parameters were made as in Rule set 1.

Fig. 3.8: Rule set 1 for the assessment of mechanical resistance and Rule set 2 for the assessment of soil aeration status.
Fig. 3.9: Rule set 3 for the assessment soil physical quality for plant production.

Rule set 3 (see Fig. 3.9) combines the effects of aeration status and mechanical resistance. Plant productivity can be alternately limited by low aeration status or by high mechanical resistance. Only if the soil aeration status is "very high" and soil mechanical resistance is "very low", the resulting physical soil quality is assessed as "good". Any deterioration of either of the two indicators is supposed to reduce physical soil quality, resulting in a rule set which allows for no compensation between the two indicators.

### 3.4.3 Assessments of soil horizons with the fuzzy logic expert system

As mentioned before, the expert system was used to assess the physical soil quality for plant production on restored soils and to compare it to nearby non-restored reference soils. The measured physical input parameters and the defuzzified output scores are given in Tab. 3.2 for the topsoil horizons and Tab. 3.3 for the subsoil horizons.
We considered only differences greater than 0.5 points in the defuzzified output score as a clear differentiation between two horizons under comparison. Looking at the topsoils, the physical quality (expressed as defuzzified score) was only marginally influenced by the restoration on four sites (difference smaller than 0.5 points), five sites showed a decrease in physical soil quality and only one site was clearly improved after restoration.

The defuzzified output score does not reflect the vagueness of the assessment. An indication of this vagueness is given by the range of possible assessments and their degree of membership in the obtained fuzzy output sets (see Fig. 3.10).
Fig. 3.10: Fuzzy output sets for the soil function "physical soil quality for plant production" of 4 non-restored reference topsoils and of the nearby restored topsoils.
On site B, a particularly low air capacity was the main reason for the poor physical soil quality of the restored soil. Site D showed an excellent condition in the reference topsoil, whereas in the restored soil all parameters had shifted to more unfavourable conditions. The low physical soil quality of site E was primarily due to the high packing density and penetration resistance. Site J featured a very special constellation of physical indicator values in the reference topsoil: High packing density combined with low penetration resistance and low air capacity associated with high saturated hydraulic conductivity. As a result, this unusual combination of indicator values led to a quality assessment in the range from "bad" to "medium", including 3 fuzzy singletons with a high degree of membership. The restored topsoil on site J showed a better performance for all indicators than the reference soil and was rated to be "rather good". This was the only topsoil with clearly improved soil physical quality after restoration.

### Tab. 3.3: Input values of measured physical parameters and crisp, defuzzified output score for restored subsoils (r) and nearby non-restored reference subsoils (nr).

<table>
<thead>
<tr>
<th>Site</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Organic carbon (%)</th>
<th>Bulk density (g cm(^{-3}))</th>
<th>Packing Density (-)</th>
<th>Penetration Resistance (MPa)</th>
<th>Air Capacity (Vol.-%)</th>
<th>Sat. Hydr. Cond. (cm d(^{-1}))</th>
<th>Defuzz. Output (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A nr</td>
<td>27.9</td>
<td>40.3</td>
<td>0.7</td>
<td>1.45</td>
<td>1.70</td>
<td>2.2</td>
<td>7.4</td>
<td>3</td>
<td>1.92</td>
</tr>
<tr>
<td>A r</td>
<td>18.8</td>
<td>37.4</td>
<td>0.8</td>
<td>1.43</td>
<td>1.60</td>
<td>4.0</td>
<td>7.5</td>
<td>4</td>
<td>2.23</td>
</tr>
<tr>
<td>B nr</td>
<td>22.2</td>
<td>39.1</td>
<td>0.5</td>
<td>1.6</td>
<td>1.80</td>
<td>3.2</td>
<td>8.0</td>
<td>18</td>
<td>2.45</td>
</tr>
<tr>
<td>B r</td>
<td>29.9</td>
<td>35.6</td>
<td>0.6</td>
<td>1.78</td>
<td>2.05</td>
<td>7.0</td>
<td>4.4</td>
<td>7</td>
<td>1.20</td>
</tr>
<tr>
<td>C nr</td>
<td>36.0</td>
<td>36.0</td>
<td>1.0</td>
<td>1.43</td>
<td>1.75</td>
<td>1.0</td>
<td>4.2</td>
<td>29</td>
<td>2.13</td>
</tr>
<tr>
<td>C r</td>
<td>22.0</td>
<td>33.0</td>
<td>0.9</td>
<td>1.58</td>
<td>1.78</td>
<td>2.0</td>
<td>6.0</td>
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<td>2.46</td>
</tr>
<tr>
<td>D nr</td>
<td>19.4</td>
<td>37.3</td>
<td>0.6</td>
<td>1.69</td>
<td>1.86</td>
<td>2.2</td>
<td>12.7</td>
<td>44</td>
<td>3.45</td>
</tr>
<tr>
<td>D r</td>
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<td>35.2</td>
<td>0.3</td>
<td>1.66</td>
<td>1.78</td>
<td>5.5</td>
<td>12.5</td>
<td>5</td>
<td>1.73</td>
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<tr>
<td>E nr</td>
<td>38.5</td>
<td>40.7</td>
<td>0.9</td>
<td>1.32</td>
<td>1.67</td>
<td>1.2</td>
<td>8.5</td>
<td>19</td>
<td>3.08</td>
</tr>
<tr>
<td>E r</td>
<td>19.9</td>
<td>32.2</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
<td>8.5</td>
<td>-</td>
<td>91</td>
<td>-</td>
</tr>
<tr>
<td>F nr</td>
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<td>32.6</td>
<td>0.3</td>
<td>1.52</td>
<td>1.8</td>
<td>4</td>
<td>8.8</td>
<td>5</td>
<td>2.03</td>
</tr>
<tr>
<td>F r</td>
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<td>33.0</td>
<td>0.6</td>
<td>1.59</td>
<td>1.87</td>
<td>4.0</td>
<td>5.1</td>
<td>5</td>
<td>1.55</td>
</tr>
<tr>
<td>G nr</td>
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<td>39.2</td>
<td>2.0</td>
<td>1.32</td>
<td>1.52</td>
<td>8.5</td>
<td>10.1</td>
<td>41</td>
<td>3.44</td>
</tr>
<tr>
<td>G r</td>
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<td>46.1</td>
<td>1.5</td>
<td>1.68</td>
<td>1.83</td>
<td>13</td>
<td>9.8</td>
<td>45</td>
<td>2.04</td>
</tr>
<tr>
<td>H nr</td>
<td>30.1</td>
<td>43.5</td>
<td>0.9</td>
<td>1.45</td>
<td>1.72</td>
<td>3</td>
<td>6.3</td>
<td>25</td>
<td>2.25</td>
</tr>
<tr>
<td>H r</td>
<td>27.5</td>
<td>41.5</td>
<td>2.3</td>
<td>1.6</td>
<td>1.85</td>
<td>6</td>
<td>8.6</td>
<td>42</td>
<td>2.04</td>
</tr>
<tr>
<td>I nr</td>
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<td>24.9</td>
<td>0.9</td>
<td>1.47</td>
<td>1.69</td>
<td>8.5</td>
<td>8.9</td>
<td>25</td>
<td>2.21</td>
</tr>
<tr>
<td>I r</td>
<td>34.5</td>
<td>58.3</td>
<td>0.4</td>
<td>1.59</td>
<td>1.90</td>
<td>2.5</td>
<td>9.0</td>
<td>35</td>
<td>3.0</td>
</tr>
<tr>
<td>J nr</td>
<td>30.0</td>
<td>27.9</td>
<td>1.1</td>
<td>1.59</td>
<td>1.86</td>
<td>3.5</td>
<td>3.8</td>
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</tr>
<tr>
<td>J r</td>
<td>23.3</td>
<td>33.6</td>
<td>1.5</td>
<td>1.7</td>
<td>1.91</td>
<td>3.5</td>
<td>7.3</td>
<td>90</td>
<td>2.17</td>
</tr>
</tbody>
</table>
For the subsoils the results were similar as for the topsoils: three out of nine subsoils tested showed a clear reduction in physical soil quality after restoration, five stayed at about the same level, and just one site exhibited clearly improved physical soil conditions.

Fig. 3.11 shows the output sets for physical subsoil quality of four non-restored and nearby restored sites. The reference soil of site B showed high mechanical resistance, but a good aeration status. On the restored soil, all parameters indicated inhibiting or limiting conditions, resulting in the lowest evaluation of all horizons. Site D featured an inhibiting packing density in the reference soil, the restored soil showed additionally a high penetration resistance and a low saturated hydraulic conductivity. On site G, all parameters except penetration resistance showed good conditions in the reference soil, whereas in the restored soil both penetration resistance and packing density were limiting factors. The low evaluation score of the reference soil of site I was mainly due to very high penetration resistance. Site I had the only subsoil with clearly improved physical quality after restoration.
Fig. 3.11: Fuzzy output sets for the soil function "physical soil quality for plant production" of 4 non-restored reference subsoils and of the nearby restored subsoils.
3.4.4 Comparison of the defuzzified output values with LLWR and S-parameter

Fig. 3.12 shows the relationships of the defuzzified output values with the least limiting water range (LLWR) and with the S-parameter. The LLWR and the S-parameter were both calculated by pedotransfer functions for the 20 topsoils of the data set. The physical soil quality assessment with the fuzzy logic expert system was highly correlated with both parameters.

\[
y = 10.887x + 2.0763
\]
\[
R^2 = 0.7955
\]

\[
y = 134.11x - 0.6802
\]
\[
R^2 = 0.6978
\]

Fig. 3.12 Relationship of defuzzified output with least limiting water range (top) and S-parameter (bottom), for the 20 topsoils of the data set.
3.5 Discussion

The close linear relationships of the defuzzified output of the fuzzy logic expert system with both the LLWR and the S-parameter allows for a comparison of the classification system and the critical limits for the three different approaches. Dexter (2004a) and Dexter and Czyz (2007) suggested to use the S-parameter as an index of soil physical quality with the following descriptive categories:

\[
\begin{align*}
0.020 > S & \quad \text{very poor} \\
0.035 > S > 0.020 & \quad \text{poor} \\
0.050 > S > 0.035 & \quad \text{good} \\
S > 0.050 & \quad \text{very good}
\end{align*}
\]

Using the regression equation relating the defuzzified output to the S-parameter (Fig. 3.12 bottom), S=0.02 corresponds to a defuzzified output value of 2.00 (“rather bad”), S=0.035 to 4.02 (“rather good”) and S=0.05 to >5.00 (“good”). In this comparison it should be taken into account that the linguistic terms are different: Dexter uses 4 categories from “very poor” to “very good”, the fuzzy logic expert system uses 5 categories from “bad” to “good”. However, for S < 0.02, both classifications classify the physical quality of a soil in the lowest category and for S > 0.05 in the highest category. Dexter and Czyz (2007) further postulated that adequate root growth typically requires values of S > 0.03, which corresponds to a fuzzy classification of 3.34 (between “medium” and “rather good”). Thus, the correspondence between the classification of the S-parameter and the fuzzy classification is very good.

Using the regression equation relating the defuzzified output to the LLWR (Fig. 3.12 top), the LLWR reaches zero at a defuzzified output value of 2.08 (“rather bad”). A LLWR of zero means that root and plant growth is limited at all soil water contents, due to high penetration resistance, insufficient aeration or inadequate water availability. On the other hand, LLWR values greater than zero signify that there is a range of a soil water contents where root and plant growth are not (or least) limited by soil physical constraints. In general, a higher LLWR is associated with better soil quality for crop growth (Leao et al., 2006). Besides this “more is better” relation, LLWR values are difficult to classify. The relationship between LLWR and plant growth has been studied by da Silva and Kay (1996). They found that the shoot growth rate of corn was optimal...
when the LLWR was > 0.15 cm$^3$ cm$^{-3}$, and reduced by approximately 20% when the LLWR was 0.1 cm$^3$ cm$^{-3}$. Using the regression equation in Fig. 3.12, a LLWR = 0.1 cm$^3$ cm$^{-3}$ corresponds to a defuzzified output value of 3.17 (“medium”) and a LLWR > 0.15 cm$^3$ cm$^{-3}$ to > 3.71 (“medium” to “rather good”), respectively. Overall, the LLWR and the defuzzified output value show a reasonable congruence.

Soil restorations are usually made under the imperative of land improvement. However, the physical quality of the investigated restored soils had rather decreased with restoration compared to the non-restored reference soils. The know-how about adequate restoration techniques and good practices of subsequent management is available, but the restoration regulations and management guidelines are not sufficiently complied with, mainly due to economic reasons. The results highlight the importance of assessing restored soil. The evaluation results should be used to enforce the existing restoration and management regulations and to formulate measures to improve physically degraded soil.

The application of our fuzzy logic expert system relies on easily measurable soil parameters. The assessment of a specific horizon is also not expensive. But given the spatial inhomogeneity of soil physical parameters, each assessment has to be considered as a point measurement and several horizons and profiles have to be assessed for an accurate evaluation of a restored site. The number of measurements to be carried out will represent a compromise between the affordable expenses and the desired accuracy of the assessment. In its present form, the expert system assesses how favourable or unfavourable soil physical conditions are for root development and plant growth. A more general fuzzy logic expert system for soil quality assessment could include more soil indicators, especially chemical and biological parameters and cover additional soil functions.

The fuzzy logic expert system uses quantitative soil data instead of a qualitative description. Therefore it suffers less from subjectivity in the input parameters than other methods. As all soil quality evaluation methods, the fuzzy logic expert system depends on vague evaluation standards. But in contrast to many other evaluation methods, a fuzzy logic approach is able to express the inherent uncertainties, to map them over the whole evaluation process from the input to the output and to visualise them in fuzzy sets. It is the strength of the fuzzy logic approach to express this ambivalence and
vagueness in the fuzziness of the results. The output set of the evaluation of a soil profile indicates the range of assessment possibilities for a given input parameter combination and not just a single assessment value. Defuzzification methods allow for the transformation of the vague output results into a crisp assessment score, as it is often required in soil quality evaluations. But the crisp score does no longer carry the valuable information about the vagueness of the statement. Therefore, results of fuzzy expert systems should always be expressed also as output fuzzy sets and not only as crisp scores.

The practical implementation of the soil quality concept can greatly benefit from the potential of fuzzy logic expert systems. The inherent vagueness of every soil quality evaluation can be modeled in a transparent way with fuzzy logic. The fuzzy membership functions and the rule base express both the system-immanent vagueness and the incomplete knowledge about how the different input parameters jointly influence the physical quality of soils. Especially in such ill-defined systems a fuzzy logic approach is much more adequate to model a reasoning process than a scheme that is based on exact specification of relationships between parameters, although the relevant processes are only partially understood.

3.6 Conclusions

Our fuzzy logic expert system gave very plausible results for the assessment of the physical soil quality of the investigated soils, as the assessments matched well with two other indicators of the physical soil quality, the least limiting water range and the S-parameter. The membership functions of the input parameters packing density, penetration resistance, air capacity and saturated hydraulic conductivity were expressed consistently among the participating experts. However, the interactions between parameters were modelled in different ways by them. Some allowed for compensation among the input parameters (i.e. if one parameter indicates good conditions and one bad conditions, the resulting soil quality was assessed to be medium) whereas others did not allow for compensation. Our rule base represents a compromise: it admits compensation between packing density and penetration resistance, aggregating the two parameters to in the parameter “soil mechanical resistance”. The same concept was used with the aggregation of air capacity and saturated hydraulic conductivity to “soil aeration status”.

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Plant growth can be restricted by high mechanical resistance as well as by low aeration status, so we assumed that no compensation is possible between these two factors. With this approach we could integrate the statements of the experts into a consistent rule base. In general, the fuzzy logic approach proved to be a very suitable tool for modelling the dependence of physical soil quality on the considered input parameters.

3.7 Acknowledgements

We thank the soil protection agency of the Canton of Zurich for permission to publish the data of the restored sites and Beyhan Aycik, Stephan Häusler, Andres Ribi, Christoph Salm and Anna Grünwald for their assistance in soil sampling, profile descriptions and soil analyses. We are also grateful to the participants of the survey. The development of the fuzzy logic expert system was only possible with their cooperation. The project was funded by the Swiss National Science Foundation (Grant No. 2100-054151.98.1).

3.8 References


Chapter 3


Fuzzy logic expert system


4

Comparison of critical limits for crop plant growth based on different indicators for the state of soil compaction

Manfred Kaufmann, Silvia Tobias, Rainer Schulin
Submitted for publication in the Journal of Plant Nutrition and Soil Science
Abstract

Soil compaction is a major problem in modern agriculture. It affects physical soil condition, in particular aeration, soil strength and water availability and has adverse effects on plant growth. Bulk density is the most frequently used indicator to describe the state of compaction of a soil. However, this parameter lacks a direct functional relationship with plant growth. Various indicators have been proposed to simultaneously characterize the state of compaction of agricultural soil and its suitability for plant growth. This paper examines and compares the critical limits for crop plant growth based on three of these indicators: packing density, least limiting water range and S-parameter (the latter is the slope of the soil water retention curve in the inflexion point). In a first step, we reviewed the literature for published optimum and limiting values of bulk density and found that these values were highly dependent on clay and silt content. Converting them into corresponding values of packing density (composite index of bulk density and clay content), a value of 1.70 was found to effectively distinguish between optimum and limiting soil conditions for plant growth. In a second step, the packing density of 59 soil horizons sampled in northern Switzerland was compared with the least limiting water range and the S-parameter of these soil horizons (both determined by means of pedotransfer functions taken from the literature). A linear relationship between the three parameters was found, which allowed for a comparison of the published critical limits for plant growth based on these parameters. The result of the comparison was that the mean value of limiting packing density corresponded to a least limiting water range of zero and to an S-value of 0.016. A least limiting water range of zero means that root and plant growth is limited independently of the soil water content. A value of the S-parameter $< 0.020$ had previously been associated with conditions where root growth is reduced to $< 30\%$ of the potential maximum growth. The critical limits of the three indicators, which had been postulated independently of each other in the literature, were found to agree well with each other. This means that all of them could equally be used to describe the compaction state of a soil and its physical suitability for plant growth. Whereas the determination of the least limiting water range and the S-parameter either require time-consuming measurements or the use of complex pedotransfer functions, packing density only requires measurements of bulk density and clay content. This makes packing
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density a very suitable indicator of physical soil quality for soil protection purposes. However, the proposed critical limits of packing density, least limiting water range and S-parameter still need further validation by field studies relating plant growth to soil compaction.

4.1 Introduction

Soil compaction is a major problem in modern agriculture. It affects physical soil condition, in particular aeration, soil mechanical resistance and water availability and has adverse effects on plant growth. Compaction decreases void space, and thereby increases the bulk density. Thus, bulk density and total porosity are the most frequently used indicators to describe the state of compaction of a soil. Several investigators reported a parabolic relationship between bulk density and crop yield, with a distinctive maximum depending on soil texture, crop and climate (Negi et al., 1981; Pabin et al., 1991; Petelkau, 1991; Czyz, 2004). A generalized relationship on how changes in bulk density influence crop yield is given in Fig. 4.1.

![Graph showing generalized relationship between plant yield and the deviation to the optimum bulk density.](image)

Fig. 4.1: Generalized relationship between plant yield and the deviation to the optimum bulk density.
However, bulk density gives little insight on the underlying soil environment that affects plant growth (Benjamin et al., 2003). Whether plant growth is adversely affected at a given bulk density depends also on many other factors, including soil texture and structure, the parent material, the climatic conditions, the organic matter content, the presence and position of a root restricting layer in the soil profile and the crop (Logsdon and Karlen, 2004). As a consequence, bulk density as a single indicator is not appropriate to describe the state of compaction and the physical suitability of a soil for plant growth (Dexter, 1997).

The main factor determining how favourable a certain bulk density value is for plant growth is soil texture. Several authors have proposed to define optimum or limiting values of bulk density strongly relating to plant growth as a function of soils texture or soil texture classes (Daddow and Warrington, 1983; Jones, 1983; Pierce et al., 1983; Pabin et al., 1991; Petelkau, 1991; USDA-NCRS, 1996). Fig. 4.2 shows optimum bulk density values in the textural triangle and Tab. 4.1 indicates the minimum bulk density value at which a root restricting condition will occur.

![Optimum Bulk Density Range](Fig. 4.2: Upper threshold values of the optimum bulk density range in tilled topsoil horizons (Petelkau, 1991).)
Methods to assess the state of compaction

Tab. 4.1: Typical values for the minimum bulk density (BD) at which a root restricting condition will occur (USDA-NRCS, 1996).

<table>
<thead>
<tr>
<th>Texture</th>
<th>Bulk density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse, medium, and fine sand and loamy sands</td>
<td>1.80</td>
</tr>
<tr>
<td>other than loamy very fine sand</td>
<td></td>
</tr>
<tr>
<td>Very fine sand, loamy very fine sand</td>
<td>1.77</td>
</tr>
<tr>
<td>Sandy loams</td>
<td>1.75</td>
</tr>
<tr>
<td>Loam, sandy clay loam</td>
<td>1.70</td>
</tr>
<tr>
<td>Clay loam</td>
<td>1.65</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>1.60</td>
</tr>
<tr>
<td>Silt, silt loam</td>
<td>1.55</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>1.50</td>
</tr>
<tr>
<td>Silty clay</td>
<td>1.45</td>
</tr>
<tr>
<td>Clay</td>
<td>1.40</td>
</tr>
</tbody>
</table>

The fact that optimum or limiting values for bulk density with respect to plant growth are different for different soils makes it difficult to use these values as general indicators for soil quality or for soil protection purposes. Legislation needs thresholds to assess the state of compaction of a soil and its suitability for crop production as indicators for soil quality. There is a need to find a single parameter for the characterization of the state of compaction of a soil that gives directly comparable values for all soils (Håkansson and Lipiec, 2000).

Several indicators have been proposed that both characterize the state of compaction of agricultural soil and its suitability for crop growth. In this study, three indicators are presented and discussed which are either easily measurable or for which pedotransfer functions for the calculation of the indicator values from easily measurable soil parameters have already been established. An early attempt to describe the state of compaction of a soil with respect to plant growth was the introduction of the concept of packing density (Benecke, 1966). Packing density (PD) was originally proposed by soil surveyors to describe and classify the state of compaction of a soil in field surveys and was included in the German soil-mapping manual (Finnern et al., 1996) and also described in DIN 19682-10 (1998). Renger (1970) defined PD as a composite index of bulk density and clay content and specified three classes of PD. Recently, PD has regained attention as an indicator for the compaction of a soil. Jones et al. (2003) used PD as an indicator of susceptibility to compaction. Tobias and Tietje (2007) compared
PD values with expert judgements on the state of compaction and the susceptibility to compaction of a variety of Swiss agricultural soils. PD was closer related to the expert judgements than bulk density or clay content alone.

Dexter (2004a) introduced a specific soil quality indicator, the so called $S$-parameter. $S$ is the slope of the soil logarithmic water retention curve at its inflection point (see Fig. 4.3). The $S$-parameter is an indicator of the amount of structural porosity (i.e. cracks, bio-pores and macrostructures). Structural porosity is important for root growth and is very sensitive to soil compaction. Dexter (2004a, 2004b, 2004c) showed that the $S$-parameter is positively correlated to root growth, soil friability and unsaturated hydraulic conductivity (at the water potential corresponding to the inflexion point) and suggests to use $S$ as an index of soil physical quality and the state of compaction. $S$ can be derived from the measured water retention curve or it can be calculated from soil texture, organic matter content and bulk density by using pedotransfer functions.

\[ \text{Fig. 4.3: Example of a soil water retention curve showing the slope (tan } \omega \text{), of the tangent to the curve at the inflexion point.} \]
Da Silva et al. (1994) introduced the concept of the least limiting water range (LLWR) as an index of the structural quality of a soil for crop growth. The LLWR is the range in soil water content, within which limitations to plant growth associated with water potential, aeration and mechanical resistance are minimal. A water content between field capacity and permanent wilting point is generally considered optimal for agricultural crop growth. According to the LLWR concept, this range can further be reduced by high penetration resistance on the dry side and by poor aeration on the wet side. Therefore, the LLWR of a soil can be directly linked to physiological limitations of plant growth (Kay et al., 2006). The LLWR becomes narrower if bulk density increases (see Fig. 4.4). If the LLWR is narrow, the likelihood is high that the soil water content falls outside the LLWR throughout the growing season with adverse effects for plant growth. Da Silva and Kay (1997, 2000) developed pedotransfer functions to predict the LLWR from bulk density, clay content and organic carbon content and proposed to use the LLWR as a tool to characterize the physical quality of a soil for crop production.

![Fig. 4.4: Least limiting water range (LLWR) of a loam (23% clay, 2.4 % OC) for bulk density values from 1 – 1.7 g cm\(^{-3}\) calculated by the pedotransfer functions of da Silva and Kay (1997). The left arrow represents the LLWR at the bulk density of 1.1 g cm\(^{-3}\), where plant growth is least limited between field capacity and the permanent wilting point. The right arrow represents the LLWR at the bulk density of 1.4 g cm\(^{-3}\), where high penetration resistance and low air capacity further reduce the LLWR.](image)
Packing density, S-parameter and LLWR can all be used as indices to describe the state of compaction of a soil in relation to crop growth, or even more general as indicators of soil quality for plant production. However, there is a lack of studies that apply the three different indicators on the same soils and analyse the quality assessments derived from the indicators for compatibility and consistency.

In the first part of this study, we tested the hypothesis that optimum (BD$_{opt}$) and limiting (BD$_{lim}$) values for bulk density reported in the literature are correlated to both clay and silt content. Then we convert the reported BD$_{opt}$ and BD$_{lim}$ values into respective values of optimum packing density (PD$_{opt}$) and limiting packing density (PD$_{lim}$) and we establish critical ranges for PD values in regard to crop growth. In the second part, we analysed a data set of 59 soil horizons to relate PD values based on direct measurements to estimates of the LLWR and S-parameter determined by means of published pedotransfer functions. Our hypothesis was that the published critical values based on the three indicators are in good agreement with each other with regard to optimum and limiting soil conditions for plant growth.

4.2 Material and Methods

4.2.1 Review of optimum and limiting bulk density values derived from literature

A literature search was done to review the relationship between bulk density and either root growth or crop yield over a wide range of soil textures. Only data sets were considered where the response of the plants to variations in bulk density was directly measured, either in field or laboratory studies. Published experimental data were taken from Czyz (2004), Daddow and Warrington (1983), Ermich and Hoffmann (1984), Jones (1983), Negi et al. (1981), Pabin et al. (1991, 1998), Petelkau (1991), and Vepraskas (1988). The studies of Daddown and Warrington (1983) and Jones (1983) are itself literature reviews. The study of Petelkau (1991) gives upper limits for optimal bulk density in a broad range of the soil textural triangle (see Fig. 4.2). These values were derived from 104 bulk density – plant growth experiments. However, the original data of these experiments was not accessible and we refer therefore to the values given in Fig. 4.2, where the optimum bulk density with maximum yield is the value given for the upper limit for optimum bulk density minus 0.1 g cm$^{-3}$ (Petelkau, 1991).
The values given in the literature were categorized in our study as “optimum bulk density” and “limiting bulk density”. The optimum bulk density of a specific soil for a specific plant can be defined in experiments according to objective criteria: it is the bulk density where either root growth, shoot growth, or crop yield is maximal. The definition of limiting bulk density values is less straightforward. Plant growth decreases continuously with increasing bulk density above the optimum level (see Fig. 4.1). In a strict sense, every condition which is not fully optimal is somewhat inhibiting or limiting. The limiting values given in the literature to which this study refers correspond to bulk densities were root growth was essentially stopped or reduced to 20% of maximum root growth.

In most studies, the percentages of clay and silt were reported. If not, they were estimated from soil texture classes. The dependence of optimum and limiting values for bulk density on clay content and silt content was analysed with multiple linear regression.

4.2.2 Soil data

Undisturbed soil samples were taken on 26 different sites from 59 topsoil horizons. All sites were located in the northern part of Switzerland. Cambisol and Gleysol were the predominant soil types. 22 sites include natural soils along planned gas pipelines that were selected in order to measure and predict the susceptibility to compaction of the soils during construction (Qasem et al, 2000). 4 sites were restored soils, of which one was a restoration plot where soil samples were taken over a three-year period in order to describe the development of soil physical parameters.

Undisturbed, structurally intact soil cores (9.2 cm diameter by 11 cm height) were taken from topsoil layers at each sampling site, using stainless steel cylinders. Three to ten replicate samples were collected in each topsoil horizon. The samples were oven dried at 105 °C for 24 hours or more until a constant weight was achieved to determine bulk density (Blake and Hartge, 1986). The dried samples were then wetted again and the aggregates crushed by hand. The slurry was wet-sieved through a 2 mm sieve in order to obtain the coarse fraction. The coarse fraction was dried at 105 °C and weighed. For the calculation of the volumetric gravel content a particle density of 2.65 g cm$^{-3}$ was assumed. Only soil horizons with volumetric gravel content smaller than 5% were used for the study. Replicate measurements of bulk density were averaged per horizon.
Soil texture was determined from bulk samples using the pipette method (Gee and Bauder, 1986). Two to four replicate measurements were taken per horizon and averaged.

Soil organic carbon was determined from bulk samples by titration with the dichromate oxidation technique (Nelson and Sommers, 1982). Soil organic matter was calculated by multiplying organic carbon content with the factor 1.724. Two replicate analyses were performed per horizon and their results averaged.

4.2.3 Calculation of packing density, least limiting water range and S-parameter

Packing density

Packing density was calculated from measured bulk density and clay content values using Eq. 4.1, as defined by Renger (1970):

\[
PD = BD + 0.009 \ C
\]  
(4.1)

where PD is packing density (\(\text{g cm}^{-3}\)), BD is bulk density (\(\text{g cm}^{-3}\)) and C is clay content (weight-%).

S-parameter

S is the slope of the soil logarithmic water retention curve at its inflection point. S is always negative, but for convenience the modulus of S is used in discussions. If the van Genuchten (1980) equation is fitted to a water retention curve, the slope at the inflection point can be calculated from the van Genuchten (1980) equation parameters. Eq. 4.2, as given in Dexter (2004a), was used for the calculation of S:

\[
S = -n(\theta_{\text{sat}} - \theta_{\text{res}}) \left( \frac{2n - 1}{n - 1} \right)^{\frac{1}{n - 2}}
\]  
(4.2)

where \(\theta_{\text{sat}}\) is the gravimetric water content at saturation, \(\theta_{\text{res}}\) is the residual water content and \(n\) is a Mualem – van Genuchten equation parameter.

Wösten et al. (1999) have derived pedotransfer functions to predict the van Genuchten equation parameters (\(\theta_{\text{sat}}, \theta_{\text{res}}\) and \(n\)) from soil survey data. The pedotransfer functions were calibrated on 5521 soil horizons from 12 European
Methods to assess the state of compaction
countries. By using these functions S was calculated from measured values of soil
texture, organic matter and bulk density.

Least limiting water range

The calculation of the LLWR requires the specification of critical limits for soil
penetration resistance and air-filled porosity in relation to crop growth. The critical
limits were selected from literature: i.e. penetration resistance at 2.5 MPa (Bengough
and Mullins, 1990; Boone, 1986; Pabin, 1991) and air-filled porosity at 10% (Carter,
1990; Lipiec and Håkansson, 2000; Reynolds, 2002; Lapen et al., 2004; Leao et al.,
2006).

The soil water content at field capacity and wilting point were calculated for each
soil horizon according to the water retention pedotransfer functions of da Silva and Kay
(1997) with bulk density, clay, and organic carbon as parameters. Similarly, the soil
water content associated with the critical value of penetration resistance (θpr) was
calculated with the soil penetration resistance pedotransfer function (da Silva and Kay,
1997). The soil water content at an air-filled porosity of 10% (θafp) was calculated as
θsat - 0.1 cm³ cm⁻³, where θsat is 1 - ρBD/ρPD, and ρBD is bulk density and ρPD is particle
density. The upper limit of the LLWR is the drier soil water content of either field
capacity or θafp, and the lower limit of the LLWR is the wetter soil water content of
either the permanent wilting point or θpr.

4.3 Results and Discussion

4.3.1 Optimum and limiting bulk density values derived from literature

Optimum and limiting bulk density values for soils of different texture were compiled
from the literature (see Tab. 4.2 and 4.3). Optimum bulk density values (BDopt) refer to
maximum root growth or crop yield and limiting bulk density values (BDlim) refer to
conditions where root growth stopped or was reduced to 20% of the maximum.

BDopt and BDlim decrease with both clay content and silt content. The regression
functions are given in Tab. 4.4 as Eqs. (4.3) – (4.6). Clay content was the dominating
factor for both the prediction of BDopt and BDlim (see Fig. 4.5) and accounted for 53%
of the variation. Eqs. (4.3) and (4.5) are similar to the regression functions reported by
Jones (1983), but the present functions are based on larger data sets.
Tab. 4.2: 35 citations from the literature of optimum bulk density ($BD_{opt}$) at given soil texture. Data source: No. 1-7 (Czyz, 2004), No. 8-12 (Ermich and Hoffmann, 1984), No. 13-32 (Jones, 1983), No. 33-34 (Negi, 1981) and No. 35 (Pabin, 1991). In addition, 29 optimal bulk density values were taken from Fig. 4.2 (Petelkau, 1991).

<table>
<thead>
<tr>
<th>No</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>$BD_{opt}$ (g cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>48</td>
<td>1.56</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>28</td>
<td>1.53</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>20</td>
<td>1.56</td>
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<td>4</td>
<td>4</td>
<td>5</td>
<td>1.60</td>
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<td>48</td>
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<td>1.50</td>
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<td>14</td>
<td>6</td>
<td>8</td>
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Methods to assess the state of compaction


<table>
<thead>
<tr>
<th>No</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>$BD_{\text{lim}}$ (g cm$^{-3}$)</th>
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<tbody>
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<td>1.80</td>
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**Fig. 4.5:** Optimum and limiting bulk density values from the literature in relation to clay content.
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Tab. 4.4: Regression equations for optimum and limiting bulk density. \( BD_{opt} \) is optimum bulk density (g cm\(^{-3} \)), \( BD_{lim} \) is limiting bulk density (g cm\(^{-3} \)), \( C \) is clay content (weight - %) and \( S \) is silt content (weight - %). Standard errors of the coefficients are indicated between parentheses.

<table>
<thead>
<tr>
<th>No.</th>
<th>Function</th>
<th>( r^2 )</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.3)</td>
<td>( BD_{opt} = 1.493 - 0.00564 \ C )</td>
<td>0.53</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.017 ) ( \pm 0.00068 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.4)</td>
<td>( BD_{opt} = 1.524 - 0.00558 \ C - 0.0000211 \ S^2 )</td>
<td>0.60</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.018 ) ( \pm 0.00063 ) ( \pm 0.0000062 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.5)</td>
<td>( BD_{lim} = 1.778 - 0.00673 \ C )</td>
<td>0.53</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.024 ) ( \pm 0.000980 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4.6)</td>
<td>( BD_{lim} = 1.816 - 0.00602 \ C - 0.0000721 \ S^2 )</td>
<td>0.66</td>
<td>p &lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.023 ) ( \pm 0.00087 ) ( \pm 0.0000188 )</td>
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</tbody>
</table>

The square of silt content was also significantly correlated to both \( BD_{opt} \) and \( BD_{lim} \) and enhanced the coefficient of determination of Eqs. (4.4) and (4.6) compared to Eqs. (4.3) and (4.4). At a given clay content, soils rich in silt have lower \( BD_{opt} \) and \( BD_{lim} \) values. This relationship was stronger for \( BD_{lim} \). When a soil is compacted to its limiting bulk density value, root growth is stopped because most soil pore diameters are smaller than the diameters of growing roots (Daddow and Warrington, 1983). A soil with a large amount of clay and silt has smaller pore diameters than a coarse-textured soil. Thus, both high clay and silt contents will lower \( BD_{lim} \) of a soil.

Considering that \( BD_{opt} \) and \( BD_{lim} \) values used for this study were determined by different field and laboratory methods and for different crops, the strong dependence of \( BD_{opt} \) and \( BD_{lim} \) with clay and silt content is remarkable. The results suggest that \( BD_{opt} \) and \( BD_{lim} \) for root and crop growth can be fairly well predicted based on clay and silt content and that Eqs. (4.4) and (4.6) are valid for different crops in different locations. However, some restrictions apply regarding the concept of optimum and limiting bulk density values:
• Optimum bulk density may vary with the climatic conditions of the growing period. Loose soils with large macro-pores can be expected to drain quickly after rainfall and may not allow to retain sufficient water to allow optimum crop growth in dry periods (McKyes, 1985). For this reason, the optimum bulk density for crop growth is often lower in wetter years, where no water stress occurs. In addition, the functional relationship that inhibits plant growth on soil looser than the optimum value is not well understood (see Fig. 4.1). The reduction in crop growth for bulk densities smaller than the optimum value is either explained with the higher probability of water stress (less capillarity) or with poorer soil-root contact that limits water and nutrient uptake (Czyz, 2004).

• Although bulk density is often closely correlated with root and crop growth, there are also studies that failed to show such a correlation (Logsdon and Karlen, 2004). Bulk density may not be a useful parameter to characterize the state of compaction in relation to crop growth of soils that are rich in clay (Dexter, 1988). Clayey soils are often highly aggregated and shrinkage can create continuous pores even if the matrix is dense. In clay soils the timing of the measurement and the water content at the time of the measurement may have great influence on the bulk density values.

• Freeze-thaw cycles and old root-channels can provide pathways for roots also in a dense soil and reduce the effect of high bulk density on crop yield. Especially no-tillage practices favour the development of a permanent system of biopores (Boone, 1988). Consequently, the limiting bulk density will be greater under no-tillage cultivation.

• Optimum and limiting bulk densities were also reported to vary significantly among plant species (Mapfumo et al., 1998). Generally, monocotyledons are less vulnerable to low porosities (or high bulk densities) than dicotyledons (Boone, 1988).

Most of the data sets used for this study refer to experiments in homogenized seedbeds at near-optimum water contents. The data set encompasses experiments with both monocotyledons and dicotyledons. As a consequence, optimum and limiting bulk density values as calculated from Eqs. (4.4) and (4.6) are not plant specific and are mainly characteristic for tilled and homogenized seedbeds at near-optimum soil water.
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Contents. Calculated values of BD_{opt} and BD_{lim} can be used as indicators of the state of compaction of a soil regarding to crop growth, or as indicators to characterize soil quality for plant production.

The linear relationships between either BD_{opt} and BD_{lim} with clay content given in Eqs. (4.3) and (4.5) allow for a transformation of BD_{opt} and BD_{lim} values into a clay-independent indicator of soil compaction by adding a correction term given as the product of clay content with the slope of the regression lines. In principle, this is the basis of the concept of packing density (PD). Eqs. (4.3) and (4.5) suggest that the coefficient of such a correction term should be about 0.0056. However, in Eq. (4.1), which defines PD, this term is given as 0.009. In the following we will use Eq. (4.1) for the transformation of the BD_{opt} and BD_{lim} values into respective optimum (PD_{opt}) and limiting (PD_{lim}) PD values, in order to adhere to the original definition of PD and to be comparable with other studies. PD_{opt} and PD_{lim} values were in the range of 1.40 – 1.85 and 1.53 – 2.05, respectively (Fig. 4.6).

![Diagram showing optimum and limiting bulk density values from the literature expressed as optimum and limiting packing density values. The packing density value of 1.7 (horizontal line) divides best between optimum and limiting packing density.](image_url)

Fig. 4.6: Optimum and limiting bulk density values from the literature expressed as optimum and limiting packing density values. The packing density value of 1.7 (horizontal line) divides best between optimum and limiting packing density.
The mean PD_{opt} value was 1.55 and the mean PD_{lim} value was 1.82. The value of 1.70 divided PD_{opt} and PD_{lim} for the whole data set fairly effectively: 60 out of 64 values for PD_{opt} were < 1.7 and 40 out of 43 values of PD_{lim} were > 1.7. Two values fall far outside the respective range of PD_{opt} and PD_{lim}: on a soil with 14% clay and 65% silt content PD_{lim} was found to be as low as 1.53. The reason for this untypical low value is that Eq. (4.1) does not include the silt content and will therefore underestimate the state of compaction in soils that are rich in silt. In the second case, the optimum packing density was as high as 1.85 on a soil with 65% clay and 17% silt content. As pointed out before, Eqs. (4.1) overestimates the influence of clay content on PD and this effect is more pronounced on soils rich in clay.

However, in the considered data set the distinction between PD_{opt} and PD_{lim} is much more evident than between BD_{opt} and BD_{lim}. This confirms the hypothesis that PD is a more suitable indicator for the state of compaction in relation to crop growth than bulk density. If the mean values for optimum and limiting PD are used to distinguish between a lower and upper range of optimum and limiting values, the following classification can be made:

- < 1.40  below optimum range of PD
- 1.40 – 1.55  lower optimum range of PD
- 1.55 – 1.70  upper optimum range of PD
- 1.70 – 1.82  lower limiting range of PD
- >1.82  upper limiting range of PD

In using the proposed classification one has to take into account that the effect of soil compaction on plant growth is gradual and no distinct threshold values can be applied. However, the classification can be used as a rough indication to assess the state of compaction of a soil in regard to plant growth. Plant growth is expected to be maximal in the center of the optimum range (i.e. around PD = 1.55) and will gradually be reduced with increasing compaction. From PD > 1.7 plant growth can be expected to be severely negatively affected.

Previous classifications based on field studies confirm our classification. Renger (1970) specified three classes for PD: low < 1.40, medium 1.40 – 1.75, and high > 1.75. Harrach et al. (1999) associated PD values greater than 1.75 with heavy compaction and
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values smaller than 1.40 with no compaction. Tobias and Tietje (2007) compared PD values with expert judgments on the state of compaction and found PD values between 1.6 – 1.8 to indicate a critical state of compaction.

4.3.2 Comparison of critical limits for plant growth based on different soil compaction indicators

As outlined in the introduction, we used the described data set of the 59 profiles from Northern Switzerland to compare the published critical limits for plant growth based on the three chosen soil compaction indicators, PD, LLWR and S-parameter. The packing density of the samples was calculated from the measured bulk density and clay content, whereas the values for least limiting water range and S-parameter were determined from other soil properties by means of pedotransfer functions (as described in the methods section). Descriptive statistics of the measured and calculated parameters of the data set are given in Table 4.5. The relationship between PD and the LLWR and between PD and the S-parameter is visualized in Fig. 4.7.

Tab. 4.5: Descriptive statistics of the measured and calculated parameters in 59 topsoil horizons.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Mean</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>SD</th>
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<tbody>
<tr>
<td>Measured parameters</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density (g cm(^{-3}))</td>
<td>p</td>
<td>1.37</td>
<td>1.38</td>
<td>0.89</td>
<td>1.64</td>
<td>0.16</td>
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<tr>
<td>Clay content (weight-%)</td>
<td>C</td>
<td>22.86</td>
<td>21</td>
<td>6</td>
<td>63</td>
<td>10.31</td>
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<tr>
<td>Silt content (weight - %)</td>
<td>SI</td>
<td>40.06</td>
<td>36</td>
<td>9</td>
<td>67</td>
<td>12.97</td>
</tr>
<tr>
<td>Organic carbon content (weight - %)</td>
<td>OC</td>
<td>2.39</td>
<td>2.4</td>
<td>0.14</td>
<td>6.7</td>
<td>1.22</td>
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<tr>
<td>Parameters derived with pedotransfer functions</td>
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</tr>
<tr>
<td>Packing density (-)</td>
<td>PD</td>
<td>1.58</td>
<td>1.56</td>
<td>1.12</td>
<td>1.84</td>
<td>0.14</td>
</tr>
<tr>
<td>Least lim. water range (cm(^{-3}) cm(^{-3}))</td>
<td>LLWR</td>
<td>0.13</td>
<td>0.14</td>
<td>0</td>
<td>0.29</td>
<td>0.07</td>
</tr>
<tr>
<td>S-parameter (-)</td>
<td>S</td>
<td>0.034</td>
<td>0.034</td>
<td>0.021</td>
<td>0.069</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Tab. 4.6: Regression equations for the relation of packing density (PD) with the least limiting water range (LLWR) and with the S-parameter (S)

<table>
<thead>
<tr>
<th>No.</th>
<th>Regression equations</th>
<th>(r^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4.7)</td>
<td>PD = - 1.6503 LLWR + 1.7928</td>
<td>0.68</td>
</tr>
<tr>
<td>(4.8)</td>
<td>PD = - 13.158 S +2.0288</td>
<td>0.63</td>
</tr>
</tbody>
</table>
Fig. 4.7: Relationship between least limiting water range and packing density, and between S-parameter and packing density in 59 soil horizons from Northern Switzerland.
Linear regression functions are given as Eqs. (4.7) and (4.8) in Tab. 4.6. The correlation between PD and LLWR ($r^2 = 0.68$) and between PD and S-parameter ($r^2 = 0.63$) were both fairly good.

In Fig. 4.7, the relation between PD and LLWR shows a bulk of points following a strong linear relationship and a number of outliers where PD for given LLWR values is smaller than it would be expected compared to the regression line. The outliers are either soils that are very rich in silt or very rich in organic matter (above the standard deviation of the data set). As stated in section 4.3.1, PD will be underestimated in soil rich in silt, as silt is not taken into account in the pedotransfer function for the calculation of PD. A high organic matter content will lower the bulk density of a soil, which will also lower the calculated PD.

The linear correlation between the packing density of the samples and the LLWR and S-parameter estimates should not be overstated, as bulk density fed into the determination of all three parameters, thus directly contributing to the correlation between them. However, this is not the crucial point of our analysis. The main point here and the reason for establishing the relationships is that they allow for a comparison of the critical limits based on the three indicators. Using Eqs. (4.7) and (4.8) and the critical limits of packing density given before (i.e. 1.40 as minimum value for optimal conditions for root and plant growth, 1.55 as average value for optimum conditions for root and plant growth, 1.70 as threshold value between optimum and limiting conditions and 1.82 as average value for limiting conditions), respective values for LLWR and S-parameter can be calculated as shown in Tab. 4.7.

**Tab. 4.7: Least limiting water range (LLWR) and S-parameter, calculated from Eqs. (4.7) and (4.8) for the critical limits of packing density.**

<table>
<thead>
<tr>
<th>Packing density (PD)</th>
<th>LLWR</th>
<th>S-parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>lower optimum range</td>
<td>1.40 &lt; PD &lt; 1.55</td>
<td>0.15 - 0.24</td>
</tr>
<tr>
<td>upper optimum range</td>
<td>1.55 &lt; PD &lt; 1.70</td>
<td>0.06 - 0.15</td>
</tr>
<tr>
<td>lower limiting range</td>
<td>1.70 &lt; PD &lt; 1.82</td>
<td>0.00 - 0.06</td>
</tr>
<tr>
<td>upper limiting range</td>
<td>1.82 &lt; PD</td>
<td>0.00</td>
</tr>
</tbody>
</table>
The LLWR reaches zero at a packing density of 1.79, which is in the lower limiting range of PD. A LLWR of zero means that root and plant growth is limited at every soil water content, either by soil penetration resistance, soil aeration or water availability. The bulk density at which the LLWR reaches zero has also been termed “critical bulk density” (Leao et al., 2006). On the other hand, every LLWR value greater than zero signifies that there exists a soil water content where root and plant growth are least limited by soil physical constraints. The probability of a soil falling outside this range of least limiting conditions throughout a growing season decreases with increasing LLWR. Therefore, a higher LLWR is associated with better soil quality for crop growth. Besides this “more is better” relation between LLWR and crop growth, LLWR values are difficult to classify. The difference of the actual water content to either the upper or lower specification limit of the LLWR is a better indicator for plant growth than the value of the LLWR itself (da Silva and Kay, 2004). However, the direct relationship between LLWR and plant growth has also been studied: da Silva and Kay (1996) reported that the shoot growth rate of corn was optimal at LLWR > 0.15 cm$^3$ cm$^{-3}$ and reduced by approx 20% at LLWR of 0.1 cm$^3$ cm$^{-3}$. This means that optimum root growth was found at a LLWR corresponding to the mean optimum value of PD and that root growth was reduced by approx. 20% at PD 1.62. This PD value is not in the limiting PD range according to our classification. However, our PD$_{lim}$ values correspond to conditions where root growth was stopped or reduced to 20% of the maximum and thus are expected to be higher than for a situation with only 20% root growth reduction. Overall, PD classes as defined in our study and the associated ranges of LLWR can be consistently related.

Dexter (2004a, 2007) suggested to use S as an index of soil physical quality with the following descriptive categories:

\[
\begin{align*}
0.020 > S & \quad \text{very poor} \\
0.035 > S > 0.020 & \quad \text{poor} \\
0.050 > S > 0.035 & \quad \text{good} \\
S > 0.050 & \quad \text{very good}
\end{align*}
\]
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Compared to our PD - classification, S = 0.020 is in the lower limiting range of PD, S = 0.035 corresponds to the mean optimum value of PD, and S = 0.050 is the lower limit of the lower optimum PD range. Dexter (2004a, 2007) further postulated that adequate root growth typically requires values of S > 0.030, and that root growth is reduced to about 30% of maximum at S = 0.020. In terms of PD this means that adequate root growth can be expected in the upper and lower optimum PD range and that root growth is reduced to 30% of the maximum from the lower limiting PD range. The correspondence between the classification of PD and the classification of the S-parameter is very good.

It is important to note that the least limiting water range and the S-parameter were calculated by pedotransfer functions that have not been validated for our data set. More research would be needed to adjust the existing pedotransfer functions to local conditions. Moreover, the critical limits based on packing density, least limiting water range and S-parameter and the relationships between them need further validation by field studies relating actually crop growth to soil compaction.

4.4 Conclusions

The results of the literature study on optimum and limiting bulk densities of soils of different textures suggest that both \( BD_{\text{opt}} \) and \( BD_{\text{lim}} \) can be satisfactorily derived by pedotransfer functions including clay and silt content. \( BD_{\text{opt}} \) and \( BD_{\text{lim}} \) values can be transformed in optimum and limiting packing density values which are not dependent on soil texture. The PD value of 1.70 is suggested as threshold value that divides between optimum and limiting conditions for root and plant growth.

Furthermore, the data from the 59 soils horizons in Northern Switzerland used in our analysis supported the hypothesis that the published critical limits for crop growth that had been established independently of each other in the literature for the three chosen soil compaction indicators (PD, LLWR and S-parameter) are in good agreement with each other. But whereas the determination of the LLWR and the S-parameter either require time-consuming measurements or the use of complex pedotransfer functions, PD can be calculated easily from bulk density and clay content. This makes PD an easily applicable general indicator of physical soil quality for soil protection purposes. Still, there is a need for further validation of these conclusions by field studies relating
soil compaction to actual plant growth. Finally it is important to note that any classification of physical soil quality based on indicators such as PD, LLWR or S-parameter represents a very rough simplification of the complex interplay of soil factors that can limit plant growth and cannot fully account for the influence of factors such as soil structure, parent material, and organic matter, considering in addition that the role of soil factors can be strongly modified by external factors, in particular climatic conditions.

4.5 Acknowledgements
We are grateful to Anna Grünwald, Werner Attinger and Beyhan Aycik for their support in field and laboratory work and to Markus Berli and Hassan Qasem for the provision of data. The project was funded by the Swiss National Science Foundation (Grant No. 2100-054151.98.1).

4.6 References
Methods to assess the state of compaction


Methods to assess the state of compaction


Development of the mechanical stability of a restored soil during the first three years of re-cultivation

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Abstract

Soil restoration is the process by which a soil that has been disturbed by excavation and displacement or by degradation is returned to its original state by means of active treatment. At the beginning of the process, restored soils are mechanically labile and susceptible to compaction. In this study, we monitored the regeneration of some physical soil quality indicators (bulk density, coarse porosity, penetration resistance) and the development of indicators of mechanical stability (precompression stress, compression index) of a refilled sandy loam originating from an Eutric Cambisol. In particular, we derived multiple linear regression equations to correlate precompression stress and compression index to soil texture, gravel content, organic carbon content and void ratio.

During the three-year observation period after restoration, bulk density and penetration resistance increased significantly, while coarse porosity decreased significantly. Nonetheless, these parameters remained in a range which is considered to indicate suitable physical soil conditions for root growth over the entire period of observation. Precompression stress increased significantly in the topsoil as well as in the subsoil. The compression index was significantly higher in the topsoil than the subsoil and stayed fairly constant over the observation period. Precompression stress was negatively and the compression index was positively correlated with initial void ratio and to coarse porosity. Taking additional parameters into account, such as gravel content, clay content, silt content and organic matter content, improved the correlation with precompression stress. The equations derived with multiple linear regression analysis from our data set gave a satisfactory coefficient of determination for the compression index ($r^2=0.81$), but a rather poor estimate for precompression stress ($r^2=0.50$).

Keywords: Soil restoration; Soil compaction; Physical soil properties; Precompression stress; Compression index
5.1 Introduction

Soil restoration is the process by which a soil is returned to its original state of functioning as part of a self-sustaining ecosystem (Harris et al., 1996). More and more soils are temporarily removed and later restored, e.g. on gravel exploitation sites, on open-cast tunnel construction sites or on landfills. Restoration does not necessarily imply regeneration of a highly productive soil. However, where soil is restored for agricultural land use, the primary goal is to re-establish a high and sustainable soil quality for plant production.

At the beginning of the process after excavation and refilling, restored soils are poorly aggregated and mechanically labile (Lebert and Springob, 1994). Over several years, they will regain strength through the development of structure (Tenholtern et al., 1996). But as long as soil structure is not well developed, these soils are highly vulnerable and susceptible to compaction. Consequently, over-compaction and waterlogging are common problems on restored soils, resulting in reduced crop growth and limitations for agricultural land management (Friedli et al., 1998).

The physical quality of a restored soil largely depends on how the soil was treated before it was put into place at the restoration site, on the way how the soil has been refilled and repacked and on the subsequent management of the regenerating soil. Suitable techniques of soil restoration and appropriate ways of soil treatment on construction sites have been proposed by many authors and in several official guidelines (Ministerium für Umwelt Baden-Württemberg, 1991; Richards et al., 1993; Häusler and Salm, 2001). In order to protect highly vulnerable restored soils, management guidelines have been elaborated with the goal to minimize mechanical disturbance of the repacked soils in the first 3 - 5 years after restoration (Harris et al., 1996; FSK, 2001). Swiss soil restoration guidelines (VSS, 2000; BUWAL, 2001; FSK, 2001) assume that if tillage and heavy traffic is avoided, restored soils regain sufficient stability within three years to allow normal agricultural land management. However, little is known about the structure regeneration process and the development of physical and mechanical properties of restored soils. There is a need for methods suited for practical applications to assess the physical quality of restored soils for plant production and their sensitivity to compaction. In this study, we evaluate parameters describing
and indicating the suitability of a restored soil for crop growth and parameters characterizing its mechanical stability against compaction.

A variety of soil parameters has been proposed as indicators for the physical quality of a soil. Larson and Pierce (1994) and Doran and Parkin (1996) included soil texture, bulk density, plant-available water capacity, hydraulic conductivity and penetration resistance in a minimum set of physical soil quality indicators. Bulk density, coarse porosity and penetration resistance are often used as indicators for assessing soil aeration and root growth conditions (Hakansson and Lipiec, 2000). However, plant growth is also highly dependent on soil moisture, and the optimum values of bulk density, coarse porosity and penetration resistance for soil aeration and plant root growth can differ with soil water regime (Letey, 1985). Low coarse porosity causes poor aeration at high soil water content, while high penetration resistance is correlated with restricted rootability at low soil water content (da Silva et al., 1994). With bulk density also the likelihood increases that poor aeration or high penetration resistance limit root and thus plant growth (da Silva and Kay, 1997).

Many authors postulate a coarse porosity of 10% as the lower limit for sufficient aeration and therefore also as the lower limit for optimal crop growth (Dexter, 1988; McAfee et al., 1989; Etana et al., 1997; Pagliai and Vignozzi, 2002). Coarse porosity values below 5-7% were found to adversely affect soil aeration and plant growth (Flühler, 1973). Various authors found that a penetration resistance of 3-5 MPa or more limited root growth (Bengough and Mullins, 1990; Canarache, 1990; Bennie, 1996; Ehlers et al., 2003). Proposed optimum and limiting bulk density values depend on soil texture (Jones, 1983; Canarache, 1991; Petelkau, 1991; Voorhees, 1992).

The mechanical stability of agricultural soils against compaction by trafficking can be characterized by its precompression stress (Horn and Lebert, 1994). The concept of precompression stress (PS) assumes that deformation is elastic (i.e. predominantly reversible) at stresses below and plastic at stresses above precompression stress. (Kirby, 1991a). Plastic deformation is irreversible and occurs along the virgin compression line (VCL). The compression index (CI) is the modulus of the slope of the VCL. Larson et al. (1980) proposed the CI of a soil as an indicator for the susceptibility to compaction. PS is sometimes interpreted as the maximum stress to which a soil had been exposed so far (Berli et al., 2001). Horn and Fleige (2003) used the ratio of PS and applied normal
stress as indicator for the susceptibility to further compaction. Both PS and CI are derived from stress-strain curves obtained from uniaxial compression tests, i.e. from the relationship between applied vertical stress and corresponding consolidation (expressed as void ratio or bulk density) in oedometer experiments.

Several attempts have been made to relate the PS to more easily measurable parameters such as texture, bulk density, Atterberg limits and organic matter content (Veenhof and McBride, 1996; Imhoff et al., 2004). Horn and Fleige (2003) have described pedotransfer functions predicting PS from soil texture, bulk density, organic matter content, soil structure, pore size distribution, cohesion and angle of internal friction at different soil water potentials. Rücknagel et al (2007) used bulk density and aggregate density to predict PS. However, these pedotransfer functions were developed for undisturbed soils and may not be appropriate for restored soils.

The objectives of this study were to (1) monitor the regeneration of physical quality indicators (bulk density, coarse porosity, penetration resistance) of a soil which had been excavated, stock-piled, back-filled and subsequently cultivated for three years according to pertinent regulations; (2) to monitor the development of precompression stress and compression index as indicators for the mechanical stability of the soil; and (3) to develop multiple linear regression equations to calculate precompression stress and compression index from soil texture, bulk density and coarse porosity.

5.2 Materials and Methods

5.2.1 Restoration and Management Operations

The experimental site was a field under which a road tunnel had been built by means of open-cast construction in the north-western part of Switzerland near Solothurn (7°34' E, 47°12' N). Top- and subsoil had been separately removed, stockpiled and repacked on top of the refilled tunnel excavation pit at the end of the construction. The bottom of the restored soil consisted of sandy loam with gravel. It was built with a slope of 2 - 3% to enable sufficient drainage. The restored soil, covering an area of several hectares, was intended to be re-used for agriculture.

The soil was rebuilt in stripes of 6 - 8 m in width. Subsoil was heaped to a height of 70 cm and covered with 40 cm of topsoil. The material was applied by a bucket excavator driving only on the bottom layer of the repacked excavation material. Thus,
top- and subsoil were restored without compaction by traffic operations. A few days after restoration was completed in autumn 1999, radish (*brassica oleara*) was sown by hand. In spring 2000 the area was mulched, ripped, harrowed and sown with a grass mixture including clover and alfalfa (*medicago sativa*). All these operations were performed with a Steyr 968 tractor of a total weight of 3985 kg. The tractor had Allianz (42x25.00-20/12 BR) front tyres and Firestone (54x37.00/25) rear tyres. The additional weight of the tillage equipment on the tractor was 650 kg. Ground contact pressure under the tyres was calculated as the ratio between wheel load and contact area and varied between 28-33 kPa. In the following years, the management was restricted to cutting and harvesting the grass two to three times a year. Cutting was executed with the same Steyr 986 tractor as before, equipped with a front mower of 820 kg, resulting in a maximum ground contact pressure under the tractor of 33 kPa. The grass was harvested in spring for silage and in summer as hay. For silage, harvest was performed with a Claas Jaguar crop chopper of 6830 kg with Conti (800/65 R 32) front tyres and Goodyear (540/65 R 23) rear tyres with a maximum ground contact pressure of 48 kPa. Hay was harvested with a hay trailer pulled by the tractor. The hay trailer did not pass over the experimental plot. Traffic was not controlled, but the whole area had been trafficked at least once by the Steyr 986 tractor in spring 2000.

For this study a 20-by-8 m experimental plot was selected in the center of the field for sampling. For this part of the field, the soil material used for restoration was originating from an Eutric Cambisol (FAO, 1990). Soil water potential was monitored by means of tensiometers on the experimental plot. Management operations were only allowed if soil water potential was below -15 kPa in the topsoil and less than -10 kPa in the subsoil (Rohr, 2002) in order to fully comply with Swiss restoration guidelines (VSS, 2000, BUWAL, 2001; FSK, 2001). It was visually confirmed that on the experimental plot trafficking did not cause tracks and rut prints deeper than a few millimetres.

### 5.2.2 Sampling and parameter determination

Soil samples were taken from the experimental plot three times per year, in spring, summer and autumn. The first sampling was carried out in autumn 1999, the last in autumn 2002. The locations of the profiles were varied at random within the
experimental plot from sampling to sampling. For each sampling, two soil profiles were
dug in the experimental plot area. From each profile, 6 - 12 samples of 9.2 cm diameter
and 11 cm height were cut out of the profile at two depths (10 - 20 cm and 40 - 50 cm),
using stainless steel cylinders. In total, 91 samples were taken from the topsoil and 94
from the subsoil during the three years of the study. The cylinders were protected with
plastic caps against disturbance during transport. The samples were stored at a
temperature of 4°C until they were analyzed individually for bulk density, coarse
porosity, gravel content, precompression stress (PS) and compression index. All these
parameters were measured for each core sample. For comparison of the development of
the parameters over time, the 6-12 replicate measurements of a sampling date were also
averaged per horizon.

The samples were saturated with water from the bottom, weighed and then
conditioned to a soil water potential of -6 kPa by means of a hanging water column.
The conditioned samples were weighed again in order to determine the drained pore
volume at a water potential of -6 kPa. We considered the drained pore volume at this
water potential as “coarse porosity”.

The conditioned soil samples were placed in an oedometer for the determination of
PS with a confined uniaxial compression test. Consolidation pressure was increased
stepwise from 8 to 800 kPa. Each pressure step was applied for 30 minutes (Berli et al.,
2001). Water was allowed to drain through the top and bottom plate of the compression
cell. The PS was determined from the experimental stress-strain curves according to the
method of Casagrande (1936). First, a tangent to the stress-strain curve is drawn at the
point of maximum curvature. Second, a bisector is drawn between this tangent and a
horizontal line trough the point of maximum curvature. Third, the intercept between the
bisector and the virgin compression line (VCL) gives the value of PS. In this study, the
tangent to the stress-strain curve at the point with maximum curvature was calculated
from the first and second derivative of a fifth-order polynom fitted to the experimental
data. The bisector line was calculated and the slope of the VCL was obtained by
regression. The points defining the VCL were determined visually. Except for the
graphical determination of the VCL, the whole procedure was performed using an
Excel-Spreadsheet. The compression index (CI) is defined as the modulus of the slope
of the VCL, plotted in a diagram of void ratio against the logarithm (base 10) of applied
stress (Smith and Smith, 1998). The CI was calculated according to the formula:
CI = \( (e^{\sigma_1} - e^{\sigma_2}) / (\log \sigma_2 - \log \sigma_1) \), where \( \sigma_1 \) and \( \sigma_2 \) are two different levels of applied normal stresses on the linear part of the stress-strain curve and \( e^{\sigma_1} \) and \( e^{\sigma_2} \) are the corresponding void ratios.

In some cases, the VCL was not linear but tended to flatten at applied stresses above 150 kPa for topsoil and above 200 kPa for subsoil samples. For the calculation of the slope of the VCL, only points on the linear part were considered. The flattening of the slope of the VCL at high stresses can be explained by the build-up of positive pore water pressures, as samples approached full saturation with increasing compaction. Although drainage was allowed to occur during compression, the results indicate that at high normal stresses the samples could not drain sufficiently within the time of one compression step (30 min). Other authors have explained the phenomena of flattening stress-strain curves at high stress levels with entrapped air (Perdok et al., 2002; Keller et al., 2004).

After the compression tests, the samples were dried at 105 °C for at least 24 hours until a constant weight was achieved and weighed to determine bulk density (Blake and Hartge, 1986). The dried samples were then wetted again and wet-sieved through a 2 mm sieve. The coarse fraction was dried at 105 °C and weighed. For the calculation of the volumetric gravel content a particle density of 2.65 g cm\(^{-3}\) was assumed.

Penetration resistance was measured in the field using a PANDA cone penetrometer (SOL SOLUTION, Riom, France) with a basal surface of 2 cm\(^2\) and a semi-angle of 30°. The instrument automatically recorded the energy of each hammer impact on the shaft and the corresponding depth of penetration. From these data it directly generated a soil penetration resistance diagram (Gourves, 1996). All measurements were taken at moisture contents close to field capacity. At each sampling, 10 penetration diagrams were taken along a transect of 2 m.

Soil texture was determined for the topsoil and the subsoil horizon individually in 2 to 4 replicate samples per sampling date, using the pipette method (Gee and Bauder, 1986).

5.2.3 Statistical analysis

The homogeneity of the experimental plot with regard to texture, gravel content and organic matter content was analysed with a Kruskal-Wallis test. The development of coarse porosity, bulk density, penetration resistance, precompression stress and
compression index between successive sampling dates was statistically analysed by a one-way analysis of variance, followed by a Tukey-Kramer HSD test with sampling date as independent variable. Variables were considered to be significantly different among sampling dates if the probability level was 0.05 or less.

5.3 Results and Discussion

5.3.1 Homogeneity of experimental plot

Tab. 5.1 and 5.2 indicate soil texture, organic matter and gravel content of the different sampling profiles within the experimental plot. Soil texture was quite homogeneous within the test site, whereas gravel content was highly variable. The averaged clay content was 20.0% and the averaged silt content 33.4% in the topsoil, respectively 18.8% and 34.2 % in the subsoil. Nonetheless, some sampling profiles differed significantly from the others, in the topsoil with respect to clay content (P<0.05), organic matter content (P<0.05) and gravel content (P<0.001) and in the subsoil with respect to organic matter content (P<0.05). Organic matter content was significantly (P<0.001) higher and gravel content (P<0.001) significantly lower in the topsoil than in the subsoil. The organic matter content did not show a clear trend over time. This observation was expected, as organic matter content is in the short term not directly related to compaction. The variability of organic matter content between different samplings appears to be dominated by spatial variability between the various sampling locations.

Tab. 5.1: Averaged values for texture, organic matter and gravel content in topsoil samples (standard deviation in parentheses).

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth (m)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Organic matter (%)</th>
<th>Gravel content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.09.1999</td>
<td>0.1 - 0.2</td>
<td>20.5 (1.25)</td>
<td>33.5 (0.91)</td>
<td>2.79 (0.40)</td>
<td>7.37 (1.08)</td>
</tr>
<tr>
<td>27.04.2000</td>
<td>0.1 - 0.2</td>
<td>21.1 (2.90)</td>
<td>34.6 (0.50)</td>
<td>2.84 (0.79)</td>
<td>8.60 (2.73)</td>
</tr>
<tr>
<td>07.07.2000</td>
<td>0.1 - 0.2</td>
<td>17.4 (0.10)</td>
<td>33.5 (0.10)</td>
<td>2.42 (0.35)</td>
<td>8.08 (2.67)</td>
</tr>
<tr>
<td>17.10.2000</td>
<td>0.1 - 0.2</td>
<td>22.4 (2.41)</td>
<td>35.1 (1.48)</td>
<td>2.84 (0.18)</td>
<td>4.61 (1.10)</td>
</tr>
<tr>
<td>31.05.2001</td>
<td>0.1 - 0.2</td>
<td>20.4 (0.96)</td>
<td>33.2 (3.71)</td>
<td>2.73 (0.18)</td>
<td>4.77 (0.87)</td>
</tr>
<tr>
<td>31.08.2001</td>
<td>0.1 - 0.2</td>
<td>20.8 (0.23)</td>
<td>33.3 (2.15)</td>
<td>2.58 (0.13)</td>
<td>5.00 (1.62)</td>
</tr>
<tr>
<td>01.11.2001</td>
<td>0.1 - 0.2</td>
<td>17.9 (0.50)</td>
<td>33.5 (0.70)</td>
<td>1.90 (0.00)</td>
<td>7.20 (0.86)</td>
</tr>
<tr>
<td>15.05.2002</td>
<td>0.1 - 0.2</td>
<td>19.4 (0.00)</td>
<td>33.2 (0.15)</td>
<td>1.74 (0.02)</td>
<td>8.56 (4.34)</td>
</tr>
<tr>
<td>11.07.2002</td>
<td>0.1 - 0.2</td>
<td>21.8 (0.10)</td>
<td>31.0 (0.10)</td>
<td>2.82 (0.03)</td>
<td>3.65 (1.32)</td>
</tr>
<tr>
<td>04.10.2002</td>
<td>0.1 - 0.2</td>
<td>18.0 (0.59)</td>
<td>32.7 (0.23)</td>
<td>1.89 (0.03)</td>
<td>8.53 (2.06)</td>
</tr>
</tbody>
</table>
Tab. 5.2: Averaged values for texture, organic matter and gravel content in subsoil samples (standard deviation in parentheses).

<table>
<thead>
<tr>
<th>Date</th>
<th>Depth (m)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Organic matter (%)</th>
<th>Gravel content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.09.1999</td>
<td>0.4 - 0.5</td>
<td>18.7 (0.88)</td>
<td>35.0 (0.58)</td>
<td>1.51 (0.28)</td>
<td>8.69 (1.43)</td>
</tr>
<tr>
<td>27.04.2000</td>
<td>0.4 - 0.5</td>
<td>17.0 (2.00)</td>
<td>32.4 (1.95)</td>
<td>0.89 (0.28)</td>
<td>13.70 (5.13)</td>
</tr>
<tr>
<td>07.07.2000</td>
<td>0.4 - 0.5</td>
<td>18.0 (0.80)</td>
<td>35.4 (0.50)</td>
<td>1.02 (0.27)</td>
<td>9.33 (1.39)</td>
</tr>
<tr>
<td>17.10.2000</td>
<td>0.4 - 0.5</td>
<td>20.1 (0.47)</td>
<td>35.2 (1.04)</td>
<td>1.10 (0.25)</td>
<td>8.47 (2.61)</td>
</tr>
<tr>
<td>31.05.2001</td>
<td>0.4 - 0.5</td>
<td>20.7 (1.50)</td>
<td>34.4 (0.15)</td>
<td>0.85 (0.26)</td>
<td>9.72 (2.13)</td>
</tr>
<tr>
<td>31.08.2001</td>
<td>0.4 - 0.5</td>
<td>18.4 (0.98)</td>
<td>35.4 (0.44)</td>
<td>0.90 (0.10)</td>
<td>11.33 (2.96)</td>
</tr>
<tr>
<td>01.11.2001</td>
<td>0.4 - 0.5</td>
<td>18.2 (0.00)</td>
<td>33.9 (0.45)</td>
<td>0.80 (0.00)</td>
<td>10.18 (3.20)</td>
</tr>
<tr>
<td>15.05.2002</td>
<td>0.4 - 0.5</td>
<td>19.2 (0.20)</td>
<td>36.0 (0.45)</td>
<td>0.98 (0.01)</td>
<td>11.58 (4.26)</td>
</tr>
<tr>
<td>11.07.2002</td>
<td>0.4 - 0.5</td>
<td>19.1 (0.10)</td>
<td>31.4 (0.10)</td>
<td>0.49 (0.00)</td>
<td>9.45 (1.64)</td>
</tr>
<tr>
<td>04.10.2002</td>
<td>0.4 - 0.5</td>
<td>18.8 (1.46)</td>
<td>34.0 (2.58)</td>
<td>0.80 (0.08)</td>
<td>7.79 (0.92)</td>
</tr>
</tbody>
</table>

5.3.2 Development of bulk density, coarse porosity and penetration resistance

Over the entire period of observation, bulk density (BD) was significantly smaller in the topsoil than in the subsoil (Fig. 5.1). Linear regression analysis over the entire period of observation indicated for both top- and subsoil BD an increasing trend over time. Topsoil BD differences between successive sampling dates were small until summer 2001. A significant increase in topsoil BD was found between summer and autumn 2001 which is attributed to compaction due to grass harvest with the Jaguar tractor which was performed for the first time in this period. In summer 2002 significantly lower topsoil BD values were found than in the samplings before and afterwards. These low BD values were related to significantly smaller stone contents in the topsoil samples and, thus, probably do not represent a change over time. Subsoil BD increased significantly from autumn 1999 to spring 2000 and showed only little variation afterwards. The increase in topsoil BD from 1.30 g cm$^{-3}$ to 1.43 g cm$^{-3}$ from start to end of the study period was significant, likewise the increase from 1.43 g cm$^{-3}$ to 1.57 g cm$^{-3}$ in subsoil BD. According to Petelkau (1991), the BD value allowing for maximum crop growth in a sandy loam (20% clay, 30% silt) is about 1.37 g cm$^{-3}$ for the topsoil and 1.47 g cm$^{-3}$ for the subsoil. Compared with these values, the topsoil was rather too loose for optimum crop growth in the beginning of the experiment, but bulk
Development of the mechanical stability of a restored soil

density was optimal at the end of the experiment. Bulk density in the subsoil was good for crop growth in the beginning and rather high at the end of the experiment.

**Fig. 5.1**: Development of bulk density, coarse porosity and penetration resistance with time. Each point represents the average of 5 to 12 replicates, error bars represent standard deviation of replicate measurements. Linear regression indicates trend of development with time.
As should be expected, coarse porosity (CP) shows opposite trends to bulk density (Fig. 5.1). Linear regression analysis indicated a decreasing trend with time for topsoil CP. Over the entire observation period, CP was significantly higher in the topsoil. In the subsoil, there was a significant decrease in the first few months, possibly due to the first trafficking of the soil as well as due to natural consolidation. After spring 2000 no clear tendency in the development of subsoil CP was visible. Topsoil CP showed a similar pattern, with a much smaller but still significant initial decrease. From beginning to end of the experiment, CP decreased significantly from 17.0 % to 13.1 % in the topsoil, and from 15.1 % to 9.0 % in the subsoil. CP values were, with very few exceptions, larger than the proposed threshold value of 10% in the topsoil. In the subsoil, CP was above 10% only at the beginning of the experiment, but it did not drop below the critical value of 5 % (Flühler, 1973).

Linear regression analysis indicated an increasing trend for the penetration resistance (PR) with time in the topsoil as well as in the subsoil. This increase in PR was more or less gradual in the topsoil over the entire observation period and only significant at the beginning of the experiment between autumn 1999 and spring 2000 (Fig. 5.1). In the subsoil, we found a significant increase in PR from summer to autumn 2000. The standard deviation of the 10 replicate measurements of each sampling date was in general very large. This may have been due to the relatively high gravel content of the soil. Initially, PR was lower in the topsoil than the subsoil. Over the entire experimental period PR increased significantly from 0.3 MPa to 1.2 MPa in the topsoil. The increase from 0.9 MPa to 1.35 MPa found in the subsoil was not significant, however. Compared to undisturbed soils (Canarache, 1990) the penetration resistances found throughout the whole study period are very low and indicate good rootability.

### 5.3.3 Development of precompression stress and compression index

Precompression stress (PS) was very low in both the topsoil and the subsoil at the beginning of the experiment (Fig. 5.2). In both depths it increased significantly from autumn 1999 to spring 2000. In the topsoil, statistically significant increases in PS were also found from spring to summer 2001, from autumn 2001 to spring 2002 and from summer to autumn 2002. In the subsoil PS remained fairly constant after the initial increase. The initial increase was considerably larger in the subsoil than in the topsoil.
By summer 2001, topsoil and subsoil reached similar PS values. Over the entire study period, PS increased from 14 kPa to 42 kPa in the topsoil, and from 17 kPa to 40 kPa in the subsoil. The PS values at the end of the study period correspond well with the maximum contact pressure (48 kPa) of the crop chopper used to perform management operations on the site. Other authors have reported PS values of 30 – 125 kPa for restored topsoils of different ages (Schneider and Schröder, 1981; Lebert and Springob, 1994). Compared to these values, PS on our study site was still very low after the three year period of restricted management. If the cultivation of the study site will be changed from grassland to crop rotation, contact pressure of agricultural machinery might reach 103
up to 200 kPa. According to the concept of PS, further plastic (i.e. irreversible) compaction is to be expected if normal stresses exceed the present PS.

The compression index (CI) was significantly higher in the topsoil than in the subsoil over the entire study period (Fig. 5.2). In the topsoil, it remained fairly constant from the beginning of the experiment until summer 2001. In autumn 2001, spring 2002 and autumn 2002 we found significant lower values than in the other samplings. These low values appeared to be related to the relatively high bulk densities of the samples. In the subsoil, CI showed a slight, but significant decrease between the first two samplings, which may have been due to the first trafficking.

5.3.4 Development of stress-strain curves

Fig. 5.3 shows the stress-strain curves of the samples taken in autumn 2000 in terms of void ratio versus logarithm of applied normal stress. The void ratio was significantly higher in the topsoil samples (solid lines) than in the subsoil samples (dashed lines) at all stresses. In general, the stress-strain curves showed a fairly parallel course. There were only few crossing overs. The curve with the lowest initial void ratio also had the lowest void ratios at higher stresses, i.e. the VCL’s of the denser samples were displaced towards lower void ratios at a given stress. This results are in contrast to classical consolidation theory developed for saturated clays, where the position of the VCL is considered as a unique property of a soil and it is expected that stress-strain curves with varying initial void ratios will eventually align on the VCL (Schmertmann, 1955). However, it has been shown before that this paradigm of soil consolidation seems not to hold true for unsaturated, aggregated soils (Culley and Larson, 1987; Kirby, 1991b). In our experiment we found that the position of the VCL in different samples (obtained at different sampling dates) of the same restored soil was strongly affected by the initial soil condition. With restoration, a soil is excavated at one place and repacked at another place. During this process the soil matrix is broken up into smaller aggregates and it is loosened and rearranged. The restored soil is then composed of relatively dense, overconsolidated aggregates but features a high inter-aggregate porosity (Rücknagel et al., 2007).
We hypothesize that upon recompression, the overconsolidated aggregates act as a frame that prevents the inter-aggregate pores from collapsing. As a result, the VCL’s of two samples with varying initial void ratios will not align because the higher initial void ratio of the looser sample is to a certain extent conserved until the precompression stress of the stabilizing aggregates is exceeded.

The transition between the recompression curve and the virgin compression line was very gradual instead of being sharp as theory postulates. This gradual transition has been reported by several authors (Berli, 2001; Arvidsson and Keller, 2004; Schäffer et al., 2007) and it is doubtful if in structured, unsaturated, agricultural soils the transition from elastic to plastic deformation really occurs at a specific stress value (i.e. the precompression stress).

Because of their similarity, the curves of the 6 to 12 replicate samples for each sampling date and depth were pooled and averaged. (Fig. 5.4).
Fig. 5.4: Compression curves for top- and subsoil at the different sampling dates. Each curve represents the average of 5 to 12 replicates.
Also these averaged stress-strain curves show only few crossing overs. However, they converge with increasing pressure. This is confirmed by linear regression which reveals a high positive correlation ($r^2=0.89$) between CI and initial void ratio for the averaged pressure-consolidation curves (Fig. 5.5). This convergence of virgin compression lines in compaction experiments was also reported by Schäffer et al. (2007), and Veenhof and McBride (1996) and is discussed in the next section.

![Graph](image)

**Fig. 5.5:** Compression index versus initial void ratio for topsoil samples (squares) and subsoil samples (circles). Each point represents the averaged value for 5 to 12 replicate samples of the same sampling date.

### 5.3.5 Correlations between parameters of soil stability and soil porosity

Initial void ratio, coarse porosity (CP), compression index (CI) and precompression stress (PS) were determined individually for each soil sample ($n=185$). Relating these parameters to each other at the level of individual samples (Fig. 5.6 and Tab. 5.3), we found positive correlations between initial void ratio and CI ($r=0.88$), between initial void ratio and CP ($r=0.82$) and between CP and CI ($r=0.81$).
Tab. 5.3: Correlation coefficients (r) between parameters of individual core samples (n=185)

<table>
<thead>
<tr>
<th></th>
<th>PS</th>
<th>CI</th>
<th>e₀</th>
<th>CP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precompression stress (PS)</td>
<td>1.00</td>
<td>-0.424</td>
<td>-0.524</td>
<td>-0.573</td>
</tr>
<tr>
<td>Compression index (CI)</td>
<td></td>
<td>1.00</td>
<td>0.885</td>
<td>0.814</td>
</tr>
<tr>
<td>Initial void ratio (e₀)</td>
<td></td>
<td></td>
<td>1.00</td>
<td>0.818</td>
</tr>
<tr>
<td>Coarse porosity (CP)</td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

Fig 5.6: Compression index and precompression stress versus initial void ratio and versus coarse porosity of all core samples (n=185).
The strong positive correlation between initial void ratio and CI is especially remarkable. According to the conventional concept of soil consolidation, CI is an inherent parameter of a soil (Larson et al., 1980) and should not be affected by compaction. In fact, some authors have shown that CI remained unaffected if samples were subjected to subsequent unloading-reloading cycles in oedometer tests (Stone and Larson, 1980; Kirby, 1991a). However, a decrease of the CI with decreasing initial void ratio (i.e. the convergence of the VCL at high stress) has also been reported by several authors (Culley and Larson, 1987; Veenhof and McBride, 1996; Silva et al., 2000; Schäffer et al., 2007). In our experiment, all samples were conditioned to a specific initial soil water tension. Within the three years sampling period, the samples got more compacted and the same soil water tension corresponded to a smaller initial water content compared to the less compacted samples at the beginning of the sampling period. The smaller soil water content of the denser samples might have lowered their CI. This explanation corresponds with the findings of Hettiaratchi (1987) and O’Sullivan and Robertson (1996) who found the CI to be dependent on soil water content. Other authors reported that CI was not affected due to variation in soil water content (Larson et al., 1980; Kirby, 1991b).

PS was negatively correlated to initial void ratio ($r=-0.52$) and to coarse porosity ($r=-0.57$). In our experiment, the soil was subjected to increasing normal stresses over time due to traffic operations, resulting in an increase in PS and a decrease in both void ratio and coarse porosity. However, Arvidsson and Keller (2004) found no correlation between soil total porosity and PS in 18 Swedish soils. Total porosity can only reflect the packing and the internal soil structure in a very homogeneous soil matrix. In this case, the mean number of grain contacts determines the mechanical stability of a soil. But in aggregated soils, the mean number of the inter-aggregate contacts is higher than the mean number of the intra-aggregate contacts (Hartge and Sommer, 1982). Total porosity (or bulk density) provides no information about this heterogeneity of soil density and is therefore poorly correlated with precompression stress (Mosaddeghi et al., 2003). Taking this into account, Rücknagel et al. (2007) introduced the ratio of aggregate density to bulk density (AD/BD ratio) as an expression to describe the amount of the inter-aggregate pores and included this parameter successfully in a pedotransfer function for the prediction of PS in aggregated soils. In their function,
increasing AD/BD ratios at a given bulk density are associated with decreasing PS. The AD/BD ratio is high in aggregated soils after tillage or mechanical loosening when many coarse pores are formed between the aggregates. We assume that in the restored soil of our study site the high coarse porosity also reflects a high AD/BD ratio, which would explain the negative correlation between PS and coarse porosity.

The negative correlation between PS and CI ($r = -0.42$) was not expected but can be explained by the negative correlation between PS and initial void ratio together with the positive correlation between initial void ratio and CI. Very similar results to ours were reported by Schäffer et al. (2007) who analysed the soil of the same site in two traffic experiments, carried out following our study.

To parameterize the positions of the virgin compression lines, we determined a hypothetical initial void ratio of normally consolidated soil at 1 kPa stress ($e_{1kPa}$) by extrapolating the virgin compression line. By plotting the $e_{1kPa}$ values against the measured initial void ratio (Fig. 5.7), we found a close relationship between the two ($r^2 = 0.90$). Like the slope also the y-intercept of the virgin compression line was highly correlated with the initial void ratio, showing that the position of the virgin compression line can be well predicted if initial void ratio is used as regressor. This is demonstrated also by the strong correlation ($r^2 = 0.90$) between the void ratio at 150 kPa normal stress and the initial void ratio (Fig. 5.8). At a pressure of 150 kPa all soil samples were found to be on the virgin compression line.

![Figure 5.7](image-url)

**Fig. 5.7:** Hypothetical initial void ratio of the normally consolidated soil at 1 kPa ($e_{1kPa}$) versus initial void ratio.
5.3.6 Multiple regression analysis for parameters of soil stability

We tested a variety of multiple linear regression models to correlate precompression stress (PS) and compression index (CI) with initial void ratio, coarse porosity, organic matter content, clay content, silt content and gravel content. We analysed the data first separately for topsoil and subsoil and then pooled together. The resulting equations of the multiple linear regression analysis are given in Tab. 4. The PS in the topsoil was negatively correlated to initial void ratio, to coarse porosity, silt content and positively related to clay content ($r^2=0.51$). Only initial void ratio and gravel content were significant predictors in the subsoil ($r^2=0.55$). Predictability was slightly better for the logarithm of PS ($r^2=0.52$ in the topsoil and $r^2=0.65$ in the subsoil). When all samples were considered, initial void ratio, coarse porosity, silt content and gravel content were negatively and organic carbon content positively correlated with PS ($r^2=0.45$) and with the logarithm of PS ($r^2=0.50$). Negative correlations between initial void ratio and PS have been reported by several authors, (Kirby, 1991b; Horn and Lebert, 1994; Berli et al., 2001; Schäffer et al., 2007). A positive correlation between organic matter content and PS has also been found by Veenhof and McBride (1996). The negative correlation between gravel content and PS is related to the fact that at a given total void ratio a higher gravel content leads to a higher void ratio of the fine-textured soil. Only if gravel

Fig. 5.8: Void ratio at 150 kPa normal stress ($e_{150kPa}$) versus initial void ratio.
contents are so high that the stones form a continuous structure providing mechanical support to the soil, an increase in PS is to be expected. The gravel content ranged between 3.7 and 13.7% in our samples. This was still far from sufficient to exert such a stability effect.

Tab. 5.4: Multiple regression analysis for compression index, precompression stress and void ratio at 150 kPa normal stress.

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<th>Multiple regression functions</th>
<th>Coefficient of determination</th>
</tr>
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<tbody>
<tr>
<td><strong>Topsoil (n=91)</strong></td>
<td></td>
</tr>
<tr>
<td>$\sigma_p = -1.584 \text{CP} - 36.244 \epsilon_0 + 0.917 \text{CL} - 2.269 \text{SI} + 141.598$</td>
<td>$r^2 = 0.51$</td>
</tr>
<tr>
<td>$\log \sigma_p = -0.029 \text{CP} - 0.483 \epsilon_0 + 0.015 \text{CL} - 0.034 \text{SI} + 3.124$</td>
<td>$r^2 = 0.52$</td>
</tr>
<tr>
<td>CI $= + 0.266 \epsilon_0 + 0.006 \text{CP} - 0.086$</td>
<td>$r^2 = 0.63$</td>
</tr>
<tr>
<td>Input value ranges: $\epsilon_0$ 0.66 - 1.19; CP 8 - 19.6%; CL 17.3 - 24.1%, SI 31.0 - 36.2%</td>
<td></td>
</tr>
</tbody>
</table>

| **Subsoil (n=94)**           |                             |
| $\sigma_p = -118.740 \epsilon_0 - 1.379 \text{GR} + 129.7$ | $r^2 = 0.55$ |
| $\log \sigma_p = -1.727 \epsilon_0 - 0.019 \text{GR} + 2.896$ | $r^2 = 0.65$ |
| CI $= + 0.006 \text{CP} + 0.106$ | $r^2 = 0.46$ |
| Input value ranges: $\epsilon_0$ 0.51 - 0.89; CP 1.8 – 18.9%; GR 5.3 - 21.0% |

| **All samples (topsoil and subsoil, n=185)** |                             |
| $\sigma_p = -59.788 \epsilon_0 - 0.745 \text{CP} + 4.873 \text{OM} - 1.147 \text{SI} - 1.277 \text{GR} + 129.17$ | $r^2 = 0.45$ |
| $\log \sigma_p = -0.818 \epsilon_0 - 0.014 \text{CP} + 0.070 \text{OM} - 0.018 \text{SI} - 0.019 \text{GR} + 2.921$ | $r^2 = 0.50$ |
| CI $= + 0.274 \epsilon_0 + 0.004 \text{CP} - 0.067$ | $r^2 = 0.81$ |
| Input value ranges: $\epsilon_0$ 0.51 - 1.19; CP 1.8 – 19.6%; GR 2.1 - 21.0% |
| OM 0.6 – 3.63%; SI 27.4 – 36.6% |

Abbreviations: CI= compression index, $\sigma_p$ = precompression stress, $\epsilon_{150\text{kPa}}$ = void ratio at 150 kPa, $\epsilon_0$ = initial void ratio, CP = coarse porosity, CL = clay content, SI = silt content, GR = gravel content, OM = organic matter content

The CI was positively correlated to coarse porosity and to initial void ratio in the topsoil ($r^2=0.63$). In the subsoil, the only significant effect was the positive correlation with coarse porosity ($r^2=0.46$). In the pooled data set, we found a positive correlation to coarse porosity and to initial void ratio ($r^2=0.81$). The positive correlation between the
CI and initial void ratio is discussed in the previous section. The positive correlation to coarse porosity reflects the high susceptibility of coarse pores to compaction. No correlation between organic matter content and CI was found. The studies of Imhoff et al. (2004), O’Sullivan (1992) and Arvidsson (1998) also revealed no significant effect of organic matter on soil compressibility in uniaxial compression tests. However, organic matter is considered to make a soil more resistant to compaction (Soane, 1990) and a negative correlation between organic matter and CI has been reported by several authors (Angers, 1990; Etana et al., 1997; Silva et al., 2000). In other studies, CI was found to be positively correlated to clay content (Larson et al., 1980; Sánchez-Girón et al., 1998; Imhoff et al., 2004), whereas in our study this correlation could not be found. The range of variation was rather small in our sampling set for soil texture and organic matter content, explaining the minor importance of these parameters in our multiple linear regression equations.

5.4 Conclusions

Comparison of the measurements of bulk density, coarse porosity and penetration resistance with literature values indicated that the state of compaction of the restored site was very low at the beginning of the measurements and close to optimum for plant growth at the end of the study period. Thus, the applied restoration technique and the subsequent careful management were very successful so far to protect the soil from excessive compaction. However, as precompression stress remained low over the entire study period, ploughing and trafficking with heavy machinery may lead to future compaction of the soil.

The observed strong positive correlation between initial void ratio and compression index is remarkable, as the compression index is often considered as an inherent parameter of a soil which should not be affected by compaction. The virgin compression lines of soil samples with differing initial void ratios did not align as would be expected if the samples had the same mechanical structure. It appears that the state of compaction of a restored soil was determined by both, the exerted stresses during wheeling operations and the initial packing after restoration. This suggests that the restoration technique has a decisive influence on the future development of the state of compaction of a soil.
The input variables used in the multiple linear regression functions did not allow for an accurate prediction of precompression stress. Additional parameters will have to be taken into account to enhance the prediction of precompression stress from basic soil properties. It remains to be explored if the inclusion of the intra-aggregate density as additional input variable would sharpen the prediction of precompression stress in restored soils.

5.5 Acknowledgements

We are grateful to the Swiss National Research Foundation (Grant No. 2100-054151.98.1) and to the soil protection agencies of the Cantons Aargau and Solothurn for supporting this project. We thank Beyhan Aycik, Anna Grünwald and Werner Attinger for technical assistance in the field and laboratory.

5.6 References


In order to address the need for an improved evaluation framework for restored soils, the specific objectives of this study were (1) to develop a methodology to assess the soil quality of restored sites and to compare the methodology with existing soil quality approaches, (2) to propose a simple indicator for the assessment of physical soil quality, and to compare the critical limits of this indicator with existing soil quality indicators, (3) to monitor the development of indicators for physical soil quality and of indicators for the mechanical stability on a site that had been restored according to pertinent regulations and (4) to develop multiple linear regression functions to derive soil precompression stress and the compaction index by basic soil properties.

6.1 Evaluation of the physical soil quality on restored sites

The concept of soil quality is a holistic view of soil and its functions within the ecosystem. It is emphasizing that soils always perform several functions simultaneously and it assumes that the effect of a specific soil indicator on one or several soil functions can be exactly determined. However, the relationship between a soil indicator to a soil functions can often not be derived strictly from scientific principles but involves subjective value judgments (Sojka et al., 2003). A fuzzy logic approach is able to express the inherent uncertainties in these value judgments, to map them over the whole evaluation process from the input to the output and to visualize them in fuzzy sets. The fuzzy logic expert system was developed for restored soils and is based on the statements of a group of soil scientists relating physical soil quality for plant productivity to packing density, penetration resistance, air capacity and saturated hydraulic conductivity. The membership functions of the input parameters were expressed consistently among the participating experts. Although the interactions between parameters were modelled in different ways by them it was possible to cover most of the experts’ opinions in a consistent rule base. The fuzzy logic expert system for the assessment of physical soil quality of restored soils gave very plausible results.
and the assessments matched well with two other indicators of the physical soil quality, the least limiting water range and the S-parameter. The fuzzy logic approach proved to be a very suitable tool for modelling the dependence of physical soil quality on the considered input parameters. It is concluded that fuzzy logic expert systems are very well suited for soil quality assessment, as they are able to express uncertainty, vagueness or even ambiguity of expert statements in a consistent system. However, some restrictions may apply in regard of the application of the results of a soil quality evaluation with a fuzzy logic expert system: the potential users of a soil quality evaluation, such as soil protection authorities, are usually not familiar with the concept of fuzzy logic and rather ask for crisp threshold values to assess soil quality and for decision making to guide management practices. Such threshold values could only be defined for the defuzzified output value of the expert system. But the defuzzified output does no longer carry the valuable information about the vagueness of the statement. Therefore, results of fuzzy expert systems should always be expressed in two ways, as fuzzy sets and as crisp, defuzzified output.

6.2 Comparison of methods to assess the state of compaction

The results of the literature study on optimum and limiting bulk densities of soils of different textures suggest that both optimum bulk density and limiting bulk density can be satisfactorily derived by pedotransfer functions including clay and silt content. Optimum and limiting values of bulk density can be transformed in optimum and limiting packing density values which are not dependent on soil texture. A packing density value of 1.70 is suggested as threshold value that divides between optimum and limiting conditions for root and plant growth.

Furthermore, the data from the 59 soils horizons in Northern Switzerland used in our analysis supported the hypothesis that the published critical limits for crop growth that had been established independently of each other in the literature for the three chosen soil compaction indicators (PD, LLWR and S-parameter) are in good agreement with each other. But whereas the determination of the LLWR and the S-parameter either require time-consuming measurements or the use of complex pedotransfer functions, PD can be calculated easily from bulk density and clay content. This makes PD an easily applicable general indicator of physical soil quality for soil protection purposes.
Still, there is a need for further validation of these conclusions by field studies relating soil compaction to actual plant growth. Finally it is important to note that any classification of physical soil quality based on indicators such as PD, LLWR or S-parameter represents a very rough simplification of the complex interplay of soil factors that can limit plant growth and cannot fully account for the influence of factors such as soil structure, parent material, and organic matter, considering in addition that the role of soil factors can be strongly modified by external factors, in particular climatic conditions.

### 6.3 Development of soil properties on a restored soil during the first three years after restoration

Comparison of the measurements of bulk density, coarse porosity and penetration resistance with literature values indicated that the state of compaction of a soil that has been restored according to pertinent guidelines was very low at the beginning of the measurements and close to optimum for plant growth after three years of controlled management. Thus, the applied restoration technique and the subsequent management system were very successful so far.

Precompression stress remained low in the topsoil as well as in the subsoil over the entire study period. Ploughing and trafficking with heavy machinery may lead to future compaction of the subsoil. Precompression stress was correlated to a number of soil parameters, but it could not be successfully derived with multiple linear regression functions from the measured input parameters. The compression index is often considered as an inherent parameter of a soil which should not be affected by compaction (Larson et al., 1980; Kirby, 1991). In contrast to these expectations, we found a strong positive correlation between initial void ratio and the compression index. As a consequence, the virgin compression lines of soil samples with differing initial void ratios did not align as would be expected if the samples had the same mechanical structure. The void ratio remained smaller for an initially dense soil at any given stress than for a less dense soil, although the difference decreased with increasing compaction. It appears that the state of compaction of a restored soil was determined by both, the exerted stresses during wheeling operations and the initial packing after
restoration. This suggests that the restoration technique has a decisive influence on the future development of the state of compaction of a soil.

6.4 Summary conclusions and outlook

The results of the evaluation of 10 restored sites and 10 adjacent non-restored soils with the fuzzy logic expert system suggest that soil restoration is often associated with a decrease of physical soil quality for plant productivity. Restoration of these sites was done without respecting the existing guidelines on using proper parent material, respecting the layering of the soil, and applying adequate restoration techniques. On the other hand, the three-year study of a site that has been restored according to existing guidelines demonstrates that good physical soil quality can be achieved if adequate restoration techniques and subsequent management techniques are applied. This is in correspondence to the observation of the Swiss Environmental Protection Agency (BAFU/BFS, 2007) who considers the uncontrolled small-scale soil restorations today as more problematic than the large-scale restorations which are planned and supervised by soil experts.

The results that were briefly summarized in chapters 6.1 – 6.3 suggest that future research should address the following topics:

- **Soil quality evaluation with fuzzy logic expert systems**

  The present evaluation system for soil restoration focuses only on physical soil quality for plant productivity. It does neither include chemical and biological parameters nor does it incorporate other soil functions. Given the susceptibility of restored soil for compaction, additional parameters for the bearing capacity of the soil to sustain agricultural management should be directly included into the system, e.g. by a comparison of the actual precompression stress of the soil with the contact pressures of the agricultural vehicles that traffic the soil. In taking more than one soil function into account, such a system would have to assess the trade-offs between potentially conflicting soil functions. However, care would have to be taken that the complexity of the system would not undermine its usefulness for decision-makers.
• **Comparison of methods to assess the state of compaction**

The results suggest that the pedotransfer function for the calculation of packing density could be improved. The given function (Renger, 1970) does not include silt content and also the organic matter content is not included. The concept of packing density would benefit a lot if both silt and organic matter content would be incorporated as well.

The least limiting water range (LLWR) and the S-parameter were calculated by pedotransfer functions that have not been validated for the soils where they were applied. As for the LLWR, there are at the moment only the functions available that were developed by da Silva and Kay (1994, 1997) for Canadian soils. A given pedotransfer function should not be extrapolated beyond the geomorphic region or soil type from which it was developed (McBratney et al., 2002). Thus, there is a clear need in further studies to measure the LLWR, and validate and adjust the existing functions to local conditions.

The S-parameter is defined as the modulus of the slope of the soil water retention curve at the inflection point. Numerous pedotransfer functions are available for the determination of the soil water retention curve. Hence, it would be interesting to test how the calculated values of S depend on the pedotransfer function selected, and to compare the calculated values with actual measurements.

• **Applying the concept of precompression stress on restored soils**

With the soil parameters considered the precompression stress could not be calculated with adequate accuracy by multiple linear regression functions. A restored soil is composed of relatively dense, overconsolidated aggregates but features a high inter-aggregate porosity (Rücknagel et al., 2007). Therefore, not only bulk density but also aggregate density should be measured and included in multiple linear regression functions in future studies. However, it is shown in the literature that precompression stress did not exactly predict the resistance against compaction on restored soil (Schäffer et al., 2007) as well as on undisrupted soils (Berli et al., 2004). The concept of precompression stress as a primary criterion to assess the soil resistance against compaction due to wheeling by agricultural vehicles will need further validation.
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Appendix

Multiple linear regression functions for the prediction of the precompression stress and the compression index from basic soil parameters

A.1 Introduction

The mechanical stability of agricultural soils against compaction by trafficking can be characterized by its precompression stress (Horn and Lebert, 1994). The concept of precompression stress (PS) assumes that deformation is elastic (i.e. reversible) at stresses below and plastic at stresses above precompression stress. (Kirby, 1991). Plastic deformation is irreversible and occurs along the virgin compression line (VCL). The compression index (CI) is the modulus of the slope of the VCL. Larson et al. (1980) proposed the CI of a soil as an indicator for the susceptibility to compaction. Horn and Fleige (2003) used the quotient of PS and applied normal stress as indicator for the susceptibility to further compaction. Both PS and CI are derived from stress-strain curves obtained from uniaxial compression tests, i.e. from the relationship between applied vertical stress and corresponding consolidation (expressed as void ratio or bulk density) in oedometer experiments.

Several attempts have been made to relate the PS to more easily measurable parameters such as texture, bulk density, Atterberg limits and organic matter content (Veenhof and McBride, 1996; Imhoff et al., 2004). Pedotransfer functions have been developed (DVWK, 1995; Horn and Fleige, 2003) predicting PS from soil texture, bulk density, organic matter content, soil structure, pore size distribution, cohesion and angle of internal friction at different soil water potentials. Rücknagel et al. (2007) used bulk density and aggregate density to predict PS. However, the application of these pedotransfer functions either requires time-consuming and expensive measuring (i.e. for aggregate density) or uncertain estimations for the input parameters. Qasem et al. (2000)
found very poor correlations when comparing measured values of PS on 21 sites with calculated values from the pedotransfer functions described in DVWK (1995).

The aim of this appendix was to investigate the relation of PS and CI to some basic and easily measurable soil parameters on restored and non restored soils and to derive multiple linear regression functions for the prediction of PS and CI.

A.2 Material and Methods

A. 2.1 Site and Soil Characterization

Totally, 1085 undisturbed soil samples were taken from 189 soil horizons of 34 different sites (see Tab. A.1). All sites are located in the northern part of Switzerland where Cambisol is the predominant soil type. Sites no. 1 – 23 encompass natural soils and are located along gas pipelines. Sites no. 24 – 34 are restored soils. All soils were classified according to FAO-Classification (1990). In the case of restored soils, we refer in our classification to the parent material that was used for restoration. The data of the sites 1-21 was compiled by Qasem et al. (2000), based on the measurements of Berli (2001).

The sites along future gas pipelines have been selected in order to measure and predict the susceptibility to compaction of the soils during pipeline construction. Additionally, on sites no. 6, 7, 8, 22 and 23, field traffic experiments of wetted and non-wetted test plots have been performed. Site 24 is a restoration plot where soil samples were taken over a three-year period in order to describe the development of soil physical parameters (see chapter 5). Sites no. 27 – 32 include restored soil profiles and nearby non-restored reference soils. Site no. 33 is a deposit of topsoil, stockpiled for further use for restoration.
Tab. A.1: Characterization of the investigated sites

<table>
<thead>
<tr>
<th>No.</th>
<th>Site</th>
<th>Soil type</th>
<th>Land use</th>
<th>Number of samples</th>
<th>No. of horizons</th>
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<tbody>
<tr>
<td>1</td>
<td>Schintbuel</td>
<td>Gleysol</td>
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<td>19</td>
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<tr>
<td>2</td>
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<tr>
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<td>Dystric Cambisol</td>
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<tr>
<td>8</td>
<td>Ruckfeld</td>
<td>Haplic Luvisol</td>
<td>crop rotation</td>
<td>113</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
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<tr>
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<td>crop rotation</td>
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<tr>
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<td>forest</td>
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<td>grassland</td>
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<td>Eutric Cambisol</td>
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<td>219</td>
<td>40</td>
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<tr>
<td>26</td>
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<td>Cambisol</td>
<td>crop rotation</td>
<td>11</td>
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<td>Gleyic Cambisol</td>
<td>grassland</td>
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<td>4</td>
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<tr>
<td>32</td>
<td>Turbenthal</td>
<td>Gleyic Cambisol</td>
<td>grassland</td>
<td>23</td>
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<tr>
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<td>Cambisol</td>
<td>deposit</td>
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<td>34</td>
<td>Andelfingen</td>
<td>Cambisol</td>
<td>crop rotation</td>
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<td>2</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>1085</strong></td>
<td><strong>189</strong></td>
</tr>
</tbody>
</table>
2.2 Sampling and parameter determination

Undisturbed, structurally intact soil cores (9.2 cm diameter by 11 cm height) were taken from two to four depths of top- and subsoil layers, using stainless steel cylinders. Three to ten replicate samples were collected at each sampling depth. The cylinders were sealed with plastic caps for transport in order to avoid disturbance of the soil.

In the laboratory, the parameters bulk density, void ratio, compression index, and precompression stress were determined for all the individual core samples (n = 1085). Coarse porosity was as well determined in the same core samples, but not on all sites (see Tab. A.2). Replicate measurements of samples from the same horizon were also averaged per horizon (n = 189). Soil texture, soil organic matter content and gravel content were determined from soil bulk samples. The methods for the determination of all the measured parameters are the same as described in chapter 5.

A.3 Results and discussion
A.3.1 Correlations between parameters of soil stability

The measured parameters, separated as individual core parameters and horizon parameters, are shown in Table A.2 with summary data on their distribution. Fig. A.1 shows the relation of the initial void ratio to the compression index and the precompression stress for all individual core samples (n = 1085) and Fig. A.2 shows the same relation for the averaged values per horizon (n = 189).

Tab. A.2: Summary data of the measured parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
<th>SD</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core sample parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk density</td>
<td>ρ</td>
<td>1.43</td>
<td>0.70</td>
<td>1.84</td>
<td>0.176</td>
<td>1085</td>
</tr>
<tr>
<td>Precompression stress</td>
<td>σ</td>
<td>67.79</td>
<td>12</td>
<td>300</td>
<td>38.40</td>
<td>1085</td>
</tr>
<tr>
<td>Compression index</td>
<td>CI</td>
<td>0.204</td>
<td>0.029</td>
<td>0.555</td>
<td>0.082</td>
<td>1085</td>
</tr>
<tr>
<td>Coarse porosity</td>
<td>CP</td>
<td>8.70</td>
<td>0.63</td>
<td>19.58</td>
<td>3.83</td>
<td>563</td>
</tr>
<tr>
<td>Horizon Parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay content</td>
<td>CL</td>
<td>23.44</td>
<td>5</td>
<td>65</td>
<td>9.41</td>
<td>189</td>
</tr>
<tr>
<td>Silt content</td>
<td>SI</td>
<td>38.26</td>
<td>8</td>
<td>67</td>
<td>10.91</td>
<td>189</td>
</tr>
<tr>
<td>Organic matter content</td>
<td>OM</td>
<td>1.95</td>
<td>0.06</td>
<td>8</td>
<td>1.37</td>
<td>189</td>
</tr>
<tr>
<td>Gravel content</td>
<td>GR</td>
<td>4.50</td>
<td>0</td>
<td>21.40</td>
<td>4.81</td>
<td>189</td>
</tr>
</tbody>
</table>

^a: Macroporosity was measured in individual core samples on sites 22-34
Fig. A.1: Relation of initial void ratio to compression index and to precompression stress in core samples \((n = 1085)\).
Fig. A.2: Relation of initial void ratio to precompression stress and to compression index calculated as averaged horizon values ($n = 189$).
In the following discussion we will only refer to the averaged horizon values of the measured parameters.

The precompression stress was poorly related to the initial void ratio. In every case, very high void ratios were associated with low precompression stresses and very high precompression stresses can be found in combination with low initial void ratios. But low precompression stress can also be associated with low initial void ratio. It was possible to draw a curve that distinguishes between likely and unlikely combinations of initial void ratio and precompression stress. Only 8 out of 189 data points were found above the curve identified in Fig. A.2.

The compression index (CI) was positively correlated ($r^2 = 0.78$) to the initial void ratio ($e_0$) in our averaged horizon values data set (see Fig A.2). After classical consolidation theory developed for saturated clays, the position of the virgin compression line is a unique property of a soil (Casagrande, 1936). Schmertmann (1953) found in uniaxial compression tests of a saturated clay, that the position of the virgin compression line was basically independent of $e_0$ and PS. On the other hand, Hough (1957) recognized the “converging pattern” of the virgin compression lines (VCL) of specimens of many different types of soils, which indicated that compressibility varies with initial void ratio. The fact that remolded virgin curves for a given soil converge at a point is also well known in geotechnical studies of clay consolidation (Rendon-Herrero, 1980). Nakase et al. (1988) made uniaxial compression experiments with saturated remolded clays of varying clay/sand mixtures and of reconstituted natural marine clays. The virgin compression lines of their specimens all converged at a single point at a void ratio of 0.3 and a mean effective stress of 14 MPa. In studies with aggregated soils, Veenhof and McBride (1996) observed this converging pattern in the majority of soil types in their study of different soils from southwestern Ontario. They pointed out that the variation in $e_0$ had a decisive effect on the configuration and positioning of the compression curves. They found a strong positive correlation between $e_0$ and CI in both plastic and non-plastic soils and concluded that the dominant influence on CI is the initial packing state of the soil. Culley and Larson (1987) found the convergence of VCL curves in uniaxial compression experiments of an undisturbed clay loam. They concluded that unsaturated VCL slopes are strongly affected by the initial soil condition. Silva et al. (2000) investigated the dependence of
the CI on initial bulk density and various saturation degrees and found strong correlations between bulk density and CI at all saturation degrees ranging from 15% to 75%. The decrease of the CI with decreasing initial void ratio has also been reported by Culley and Larson (1987) and by Schäffer et al. (2007). Our own results confirm the major influence of the initial packing state of a soil on the compression index.

A. 3.2 Multiple linear regression analysis for precompression stress and compression index

Multiple linear regression functions for PS and CI are shown in Tab. A.3. We first tested initial void ratio, soil texture, organic matter and gravel content as input parameters for the regression functions, because they were measured in all horizons. In a second step, also coarse porosity was included, which was only measured on 113 of the 189 horizons.

Tab. A.3: Multiple linear regression functions for the compression index and for precompression stress.

<table>
<thead>
<tr>
<th>No.</th>
<th>Multiple linear regression functions</th>
<th>r²</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.3</td>
<td>CI = 0.2862 + 0.2398 e₀ – 0.0009 SI</td>
<td>0.80</td>
<td>189</td>
</tr>
<tr>
<td>A.4</td>
<td>CI = –0.0720 + 0.3086 e₀ + 0.0026 CL – 0.0011 SI</td>
<td>0.87</td>
<td>153</td>
</tr>
<tr>
<td>A.5</td>
<td>CI = –0.0673 + 0.2926 e₀ + 0.0028 CP</td>
<td>0.88</td>
<td>113</td>
</tr>
<tr>
<td>A.6</td>
<td>log PS = 1.9662 – 0.4071 e₀ + 0.0051 CL + 0.0038 SI – 0.0250 GR</td>
<td>0.46</td>
<td>189</td>
</tr>
<tr>
<td>A.7</td>
<td>log PS = 2.0230 – 0.2391 e₀ + 0.0078 CL – 0.0256 CP – 0.0173 GR</td>
<td>0.51</td>
<td>113</td>
</tr>
</tbody>
</table>

Abbreviations: initial void ratio (e₀), clay content (CL), silt content (SI), coarse porosity (CP), gravel content (GR).

Precompression stress

The logarithm of PS was negatively correlated to initial void ratio and gravel content and positively correlated to clay and silt content. However, the coefficient of determination of the regression equation (see Eq. A.6) was only 0.46. The negative correlation to initial void ratio, although not very strong, is visible in Fig. A.2. Others have also reported a similar relationship: Kirby (1991) found PS of vertisols from
Australia to be dependent on the void ratio and the moisture content. In his study, PS was negatively related to the void ratio at PS. Alexandrou and Earl (1998) described a linear relationship between bulk density and PS on a sandy loam soil. In contrast, Arvidsson and Keller (2004) found no correlation between total porosity and PS in 18 Swedish soils. Total porosity provides no information about the differences between inter-aggregate and intra-aggregate porosity and is therefore poorly correlated with PS (Mosaddeghi et al., 2003). We found a positive correlation between log PS and clay and silt content. Soils that are rich in clay and silt have at a given bulk density (or void ratio) a higher packing density that soils that are poor in clay and silt, because the average pore radii are smaller (compare chapter 4.3.1). This higher packing density might also be reflected in a higher PS. The negative correlation of PS to gravel content could be due to a stabilizing effect of stones that can prevent the soil matrix from compaction.

Eq. A.7 includes coarse porosity as prediction variable of PS. Coarse porosity was negatively correlated to PS and enhanced the coefficient of determination of the equation to 0.51. Coarse pores are most susceptible to compaction and are most affected by compression. As expected, soils with high PS tend to have low coarse porosity.

Compression index

Among the considered input parameters (initial void ratio, clay content, silt content, organic matter and gravel content), initial void ratio and silt content were the only significant predictors for CI ($r^2 = 0.80$), see Eq. A.3 in Tab. A.3). While the positive correlation between CI and initial void ratio was expected from the results presented in the previous section, the significant negative correlation between CI and the silt content was rather surprising and counterintuitive, as silty soils are often described as specifically prone to compaction (Tenholtem, 1996; Teiwes, 1988). In our data set, the silt content was positively related to the logarithm of precompression stress (PS). This is an indication that the soils with high silt content were already more overconsolidated compared to soils with low silt content, a fact that may partially explaining the impact of silt content to CI.

Organic matter content (OM) had no significant effect on CI. Generally, OM is considered to make a soil more resistant to compaction (Soane, 1990). An increase in OM has been reported by several authors to reduce the soil compressibility (Silva et. al,
2000; Etana et al, 1997; Angers, 1990). However, the studies of Imhoff et. al (2004), O’Sullivan (1992), and Arvidsson (1998) also revealed no significant effect of OM on soil compressibility in uniaxial compression tests.

Soil compressibility has been reported by several authors to be positively related to clay content (Etana et al. 1997; Arvidsson, 1998, Sánchez-Girón et al., 1998). Larson et al. (1980) found a positive linear relationship between the clay content and the compression index. CI increased up to clay contents of about 33% and then leveled off. These findings were true for clay types of both temperate region soils and highly weathered soils. Imhoff et al. (2004) found in Oxisols a linear increase of CI with clay content up to a value of 30%, while the CI remained relatively constant thereafter. Angers (1990) described a positive correlation between clay content and CI for soils with <35% clay and a negative correlation for soils with >35% Clay. Sánchez-Girón et al. (1998) found a positive correlation between clay content and the CI, when the moisture content was greater than 20%. They postulate that clay acts as lubricant between sand particles, thereby increasing soil compressibility, once a certain moisture content close to the plastic limit is reached. Veenhof and McBride (1996) reported a positive correlation of clay content and CI and included clay content as significant parameter in a multiple regression equation for the prediction of the CI of structured non-plastic soils. In accordance to these authors we found a positive correlation between clay content and CI when we excluded horizons with clay contents above 30% from our data set. The corresponding multiple linear regression function (n = 153) includes initial void ratio, clay content and silt content as significant predictors for CI ($r^2 = 0.87$) see Eq. A.4 in Tab. A.3).

Coarse porosity was positively correlated to CI and inclusion of coarse porosity (n=113) slightly enhanced the prediction of CI ($r^2 = 0.88$), see Eq. A.5 in Tab. A.3. High coarse porosity is associated with high initial void ratio and the same considerations as in the previous section apply.

A.4 Conclusions

The paradigm of the classical consolidation theory, that the position of the virgin compression line is a unique property of a soil, seems not to hold true for unsaturated, aggregated soils. Instead, the initial density of the packing of the soil has a decisive
influence of the compression index. As a consequence, the compression index can be satisfactorily derived from easily measurable soil parameters.

On the other hand, soil precompression stress could not be derived with sufficient accuracy from the linear regression functions that we developed. However, the coefficient of determination between measured and predicted values of the precompression stress was similar as in the study of Qasem et al. (2000) when using the pedotransfer functions as defined by DVWK (1995).

A.5 Acknowledgements

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A.6 References


Appendix


Curriculum Vitae

Person
Surname : Kaufmann
First name : Manfred
Date of birth : 16 January 1967
Citizen of : Ehrengen and Horw, Switzerland

School education
1974 – 1979 Primary school in Unterehreningen
1979 – 1983 Secondary school in Baden
1983 – 1987 Gymnasium in Baden, Matura Typus C

Education and professional experience
1994 – 1998 Ernst Basler and Partners, Zollikon, Consulting engineers, project management of environmental impact assessment studies
1999 – 2008 PhD-student and teaching assistant, Institute of Land Improvement and Water Management, Institute of Terrestrial Ecosystems, ETH Zurich
2004 – present Scientific Assistant and Programme Manager North-South Centre of ETH Zurich