Soil quality assessment
in rice production systems

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Dedicated to:
Farmers from "Banhado do Colégio".

Abstract

In the state of Rio Grande do Sul, Brazil, rice production is one of the most important regional activities. Farmers are concerned that the land use practices for rice production in the Camaquã region may not be sustainable because of detrimental effects on soil quality. The study presented in this thesis aimed (a) to describe and understand how rice farmers assess soil quality; (b) to propose a minimum data set (MDS) to assess soil quality; (c) to establish which soil quality indicator(s) can be used to guide management leading to sustained crop production and (d) to reconcile local and scientific knowledge. To accomplish these objectives the research was based on two methodological procedures to assess soil quality: qualitative (local knowledge) and quantitative (scientific knowledge).

The qualitative study led to the understanding of soil quality from a rice farmers' perspective. Farmers from Camaquã were found to have detailed knowledge and a holistic view of the quality of the soil they are cultivating. Eleven indicators were mentioned as good soil quality indicators. Four out of these 11 soil quality indicators were considered "significant" by the farmers (soil colour, earthworms, soil organic matter and soil friability), while three indicators were found to be "useful" by the farmers in their decision-making: spontaneous vegetation, rice plant development and soil colour.

In order to assess soil quality following a scientific approach, the three main management systems for irrigated rice in Rio Grande do Sul were chosen: conventional (dry seedbed preparation and sowing, high tillage intensity), semi-direct (dry seedbed preparation and sowing, low tillage intensity), and pre-germinated (seedbed preparation and sowing on inundated fields, high tillage intensity). Twenty-one rice fields covering these management systems and two different soil great groups were selected for investigation. In each field, five replicate plots were randomly laid out within an area of 3 ha for sampling. From each plot, 29 soil properties were analysed to establish a MDS using statistical tools in a novel way. The MDS consists of eight significant soil quality indicators: available water, bulk density, mean weight diameter, organic matter, Zn, Cu, Mn and earthworm number. In order to define the usefulness of this scientific approach, and to compare this with the local knowledge, a soil quality index (SQI) was determined. This study demonstrated that soil quality was best assessed when using the entire indicators set of 29 indicators. However, the MDS and farmers' indicators sets performed almost equally well as the entire indicators set in showing the same trends in differences between management systems, soil textural classes and soil functions. The semi-direct management system resulted in the highest overall SQI, followed by the pre-germinated and conventional systems. A further study was undertaken to assess the effects of the different rice management systems on the physical and chemical soil quality. The results also indicate that the semi-direct management system is more sustainable, whereas the pre-germinated and conventional systems appear to contribute to soil degradation. Finally, a review of the state of knowledge on earthworm diversity in Rio Grande do Sul revealed 36 species and 20 genera, belonging to a total of 7 families in the state. Nine species were found in the rice fields of Camaquã (all new records for the region), two species were reported for the first time for the Rio Grande do Sul state and a new native genus and species of Criodrilidae (*Guarani camaqua*) was described.

It is concluded that statistical procedures identified soil quality indicators which can be applied to monitor soil quality of rice fields and to support management decisions. Using an integrated approach may therefore increase the understanding of the complex nature of soil.

Contents

Chapter 1

General introduction

1.1. Soil quality

Many definitions of soil quality have been proposed (Doran and Parkin, 1994; Larson and Pierce, 1994). Common to all the definitions is the capacity of soils to function effectively at present and in the future. An expanded version of this definition presents 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" (Karlen et al., 1997). However, no soil is likely to provide all these functions, some of which occur in natural ecosystems and some of which are the result of human modification (Govaerts et al., 2006).

Soils have an inherent quality as related to their physical, chemical and biological properties within the constraints set by climate and ecosystems, but the ultimate determinant of soil quality is the land manager (Doran, 2002). Perceptions of what constitutes a good soil vary depending on individual priorities with respect to soil function, intended land use and interest of the observer (Doran and Parkin, 1994, Shukla et al., 2006). Within the framework of agricultural production, high soil quality equates to maintenance of high productivity without significant soil or environmental degradation (Govaerts et al., 2006).

The assessment of soil quality can be viewed as a primary indicator of the sustainability of land management (Doran, 2002). Basically, two types of approach are employed for evaluating the sustainability of a management system: (i) comparative assessment and (ii) dynamic assessment. A comparative assessment is one in which the performance of the management system is evaluated in relation to alternatives at a given time only. In contrast, in a dynamic approach, the management system is evaluated in terms of its performance over time (Larson and Pierce, 1994).

In any case, the agricultural community (scientists, farmers, rural extensionists) needs standards of soil quality to determine what is good or bad and to find out if soil management systems achieve acceptable levels of performance. The present study aims to assess soil quality using a comparative assessment.

1.2. Soil quality assessment

Farmers' knowledge of soil quality, based on their ability to perceive differences between and within fields, is widely recognized. Using interviews and/or participatory approaches, many studies have highlighted the potential of local soil knowledge for sustainable soil management (Roming et al., 1996; Lefroy et al., 2000; Doran, 2002; Ali, 2003; Pulido and Bocco, 2003; Barrios and Trejo, 2003; Ericksen and Ardón, 2003; Barrios et al., 2006). Although benefits of local knowledge include high local relevance to complex environmental interactions, local definitions and observations can be inaccurate and unsuitable to address environmental change without scientific input (Barrios and Trejo, 2003).

Hence, an approach will be followed in the present study, in which farmers' knowledge and formal scientific knowledge will be reconciled and evaluated to both achieve local relevance and to overcome the limitations of site-specificity and empirical nature and allow knowledge extrapolation through space.

Soil quality cannot be measured directly; it must be inferred from a wide range of soil quality properties (physical, chemical and biological) that influence the capacity of soil to perform a function. However, a generic set of basic properties, commonly known as soil quality indicators, has not been agreed upon, largely due to the difficulty in defining and identifying what soil quality represents and how it can be measured. Identification of indicators and assessment approaches are further complicated by the multiplicity of physical, chemical and biological factors that interact and control soil functions and their variation in intensity over time and space (Doran and Parkin, 1996). Moreover, to objectively and simultaneously consider the outcomes of all the soil quality indicators for all three major performance indicators – production, sustainability and environmental impact – is a difficult task (Sojka and Upchurch, 1999).

One way to integrate information from soil indicators into the management decision process is to develop an integrated soil quality index (Mohanty et al., 2007). The Productivity Index (PI) model of Kiniry et al. (1983) is the basis of many approaches to assessing soil quality. The model is a multiplicative model that integrates field measurements of the soil indicators into an index that relates to plant productivity. Kiniry et al. (1983) chose five soil indicators to include in their PI model (1) available water storage capacity, (2) bulk density, (3) aeration, (4) pH and (5) electrical conductivity. The selection of only five soil indicators was a deliberate attempt to consider only the minimum set that might describe the chemical and physical nature of the rooting zone. Response curves relating root growth to soil indicators were developed from studies selected for the best measure of individual soil indicators. Each response curve was converted into a form that predicted the fractional sufficiency of that indicator for root growth. The PI was then calculated according to equation [1].

$$PI = \sum_{i=0}^{d} \left(A \times B \times C \times D \times E \times RI \right)_i \qquad [1]$$

where A, B, C, D, and E are values determined from sufficiency relationships developed for each indicator with respect to root growth, RI is a weighting factor based on the ideal root distribution, and i represents soil horizon or layer.

Further to the basic principle of the PI model, other models to integrate soil measurement values into a single assessment of soil quality were proposed by Pierce et al. (1983), Gale et al. (1991), Burger and Kelting (1999) and others. The one most commonly adopted is the additive model of Karlen and Stott (1994), because of its flexibility and ease of use. They selected soil functions associated with soil quality to evaluate the effects of different types of soil management. These functions were weighted and integrated according to equation [2]:

$$\textit{Soil Quality Index} = q_{we}\,(wt) + q_{wt}\,(wt) + q_{rd}\,(wt) + q_{spg}\,(wt) \qquad [2]$$

where q_{we} is the rating for the soil's ability to accommodate water entry, q_{wt} is the rating for the soil's ability to facilitate water transfer, q_{rd} is the rating for the soil's ability to resist degradation, q_{spg} is the rating for the soil's ability to sustain plant growth, wt is the numerical weight for each soil function. The relative weights represent the importance of each attribute in determining soil quality on a given site, and they are assigned based on the literature, experimentation or professional expertise.

Although these models have proven to be valuable, the subjective choice of the soil functions, soil indicators, the possibility of correlations among them and the use of weighting factors may be considered disadvantages. An approach to more objectively assess soil quality is evaluating several soil indicators simultaneously using statistical procedures that account for correlations. Multivariate statistical methods are used to select a minimum data set (MDS) from large data sets. In this way just few indicators have to be determined to assess soil quality. Various such MDSs have been proposed at plot and field scales (Doran and Parkin, 1996), on a regional scales (Brejda et al., 2000a,b) and on a national scales (Sparling and Schipper, 2002; Sparling and Schipper 2004; Sparling et al., 2004). The use of this approach has shown the potential to integrate biological, chemical and physical data. As a result, the concept of a MDS of soil quality indicators has become widely accepted as the minimum needed to effectively monitor soil quality and to simplify interpretation in terms of sustainable land use, while reducing costs. Yet, methodologies to arrive at MDSs are the subject of ongoing discussions (Wander and Bollero, 1999, Brejda et al., 2000a,b, Sparling and Schipper, 2002, Govaerts et al., 2006, Rezaei et al., 2007).

The present study takes the debate further in presenting an approach based on farmers' and formal scientific knowledge in rice management systems in southern Brazil. I suggest that my approach has wide applicability for improving land management decisions towards sustainable agriculture.

1.3. Main characteristics of the study (area)

The study was conducted in a community known as "Banhado do Colégio", located in the municipality of Camaquã, Rio Grande do Sul state, Brazil. The region is situated between latitudes 30º48' and 31º32' S, and longitudes 51º47' and 52º19'W (Figure 1). Mean annual rainfall is 1213 mm and the average temperature is 18.8ºC (Cunha et al., 2001). The two soil great groups found in this region are Albaqualf and Humaquepts (Soil Survey Staff, 2006). One of the main differences between and within these soils is the inherent clay content found in the topsoil (Cunha et al., 2001).

The history of the community goes back to the first Brazilian land reform in 1959. When the community was founded in the early sixties, the area was a swamp, which was drained, and approximately 200 families started farming. The lots (10 – 25 ha each) were gradually distributed to landless family farmers. These families were mainly descendants of German and Polish settlers who immigrated to Brazil in the end of the 19th century (Westphal, 1998; Ferreira, 2001). The inherent fertility of the soils was the most important reason to attract farmers to the community in the end of 1960s. The total area of the community is 4900 ha, mostly characterized by fields that are not very suitable for crops other than irrigated rice. Rice production was started soon after the start of the community. Since then, the same fields are still used for agricultural production, but with increased use of external inputs (seeds, pesticides, fertilizers, etc.), and increased use of water and intensification in soil preparation (Cunha et al., 2001). As a result, the rice production level can reach records of 9 Mg.ha^{-1}.

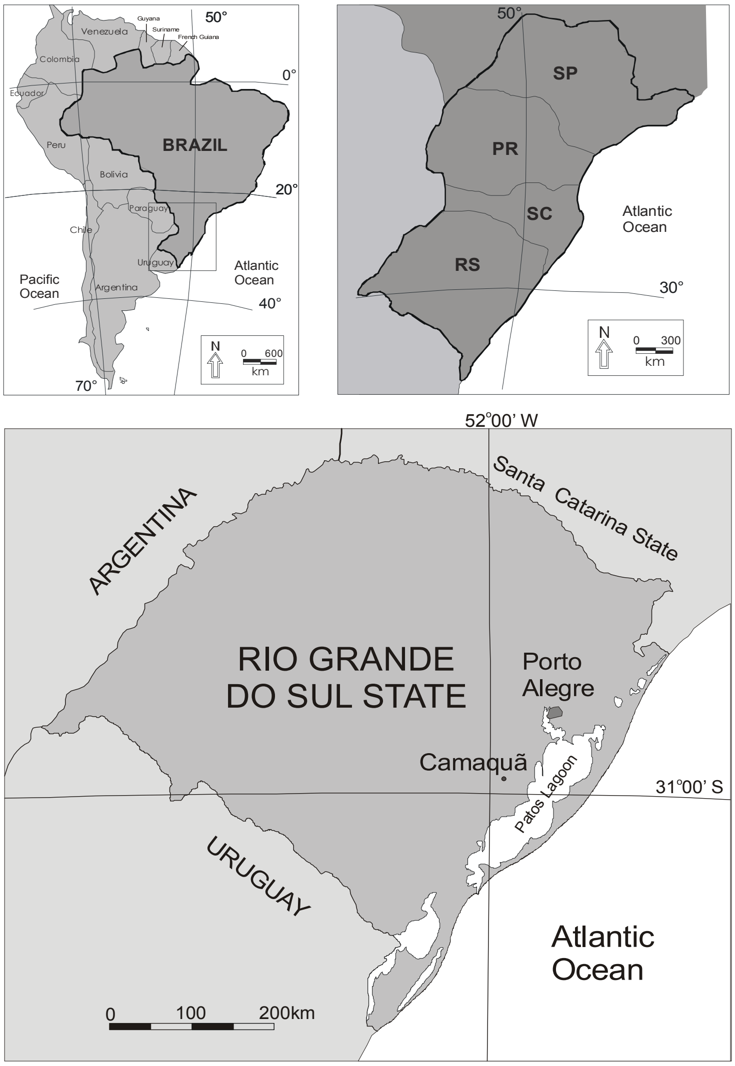

Figure 1. Location of the study area

The area of the study was selected because the farmers use the three main irrigated rice management systems adopted in Rio Grande do Sul: conventional, pre-germinated and semi-direct. The systems are different with respect to intensity and timing of soil tillage and water use. The differences are described in detail in the next chapters.

There is a large variation of farm sizes (2-500 ha) in the region. In general, this settlement consists of small and medium-sized farms. The farmers are commonly willing to exchange experiences in order to achieve better livelihoods. According to Fernandes (2004), small farmers have better ability to handle difficulties and achieve high land productivity while having less support and resource than big farmers. The study of local knowledge took place at the farmer's house or in his/her field. Out of the 200 active rice farmers in the region, 50 were chosen to be interviewed based on the following criteria: (a) farmers should own and work on the fields themselves in order to minimize misunderstandings due to limited knowledge of the soil or the management systems; and (b) the three management systems had to be represented. After contacting potential farmers, 32 of them were interviewed (3 using the conventional management system, 13 using the pre-germinated system, and 16 using the semi-direct system) because not all farmers were ready to spend the necessary time or were interested in participating in the study. The number of farmers interviewed who use the conventional system is low, because it was not possible to find more than 3 fields in Banhado do Colégio, where the conventional system is applied.

Details on the sampled fields and soil and plant properties measured will be given in the next chapters.

1.4. Problem statement and objectives

Although considerable activity is currently aimed at assessment and evaluation of soil quality, what constitutes a good indicator (set), how to arrive at a MDS and how to use it for sustainable land management are all matters of scientific development and debate. I, therefore, formulated the problem statement as follows:

What basic measurements and procedures should we (as soil scientists co-operating with farmers) carry out, that will help us evaluate the effects of management on soil function now and in the future?

At a practical level, the incentive to this study is that land use practices in rice production systems in the Camaquã region of south Brazil may not be sustainable because of detrimental effects on soil quality.

Given the state of the art described above, the main objectives of this study are:

a. To understand and describe how rice farmers assess soil quality (local knowledge)
b. To propose a minimum data set to assess soil quality (scientific knowledge)
c. To establish which soil quality indicator(s) can be managed in view of sustained production
d. To reconcile local and scientific knowledge

1.5. Outline of the thesis

In **chapter 1** I give an overview of the present knowledge about soil quality and how it can be assessed. I also introduce the research area and main features of the study, define the problem and objectives of the research and outline the thesis. In **chapter 2** I report how farmers assess soil quality in rice production systems, using a qualitative methodological procedure based on individual semi-structured interviews and discussion groups. In **chapter 3** I use multivariate analysis of 29 soil quality indicators in a novel way to arrive at a MDS to assess soil quality. In **chapter 4** I compare soil quality indices based on three sets of indicators: farmers' indicators, the MDS and the entire data set to evaluate the strong and weak points of each. In **chapter 5** I further investigate the effects of the different rice management systems on physical and chemical soil quality. Special attention to this matter is motivated from the fact that in the lowland soils in the state of Rio Grande do Sul the degradation problems linked to the nature of the soils (deficient drainage) are intensified by agricultural activity. Because to the supposed importance of earthworms for the quality of the soil and the absence of recent earthworm diversity literature of the region, I present in **chapter 6** the state of knowledge of earthworm diversity in Rio Grande do Sul and describe a new native criodrilid genus and species, found in the rice production systems. Finally, I present a general discussion and synthesis of my research in **chapter 7**.

Chapter 2

Farmers' assessment of soil quality in rice production systems

Abstract

In the recent past, there has been an increasing recognition of the notion that local knowledge of farmers can yield insight into soil quality. With regard to constraints and possibilities for the production of irrigated rice in the south of Brazil there is no documentation on local soil knowledge. The goals of this research were to answer the following questions: (1) What soil quality perceptions do rice farmers have? (2) Which soil quality indicators are the most important for them? (3) Do rice farmers use their knowledge about soil quality indicators for guiding soil management decisions and development of sustainable management? The study was carried out in the municipality of Camaquã, Rio Grande do Sul state of Brazil. Semi-structured interviews alternated with discussion groups were chosen as research methods. The outcome of the study revealed that farmers' perceptions of regional soil quality were closely related to visible environmental and economic factors. Eleven indicators were mentioned as good soil quality indicators: earthworms, soil colour, yield, spontaneous vegetation, soil organic matter, root development, soil friability, rice plant development, colour of the rice plant, number of rice tillers and cattle health. Out of these, three indicators were found to be useful in farmers' decision-making: spontaneous vegetation, rice plant development and soil colour. The potential use of local knowledge for maintenance of soil quality and development of sustainable land management is discussed.

Keywords: Brazil; local soil knowledge; rice; soil quality indicators.

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2.1. Introduction

The success of maintaining or enhancing soil quality depends on our understanding of how soil responds to agricultural use and practices. Concern for soil quality is not limited to agricultural scientists, natural resource managers, and policymakers, but farmers also have a vested interest in soil quality (Gregorich et al., 1994; Roming et al., 1995). A growing number of ethnopedological studies on local soil knowledge has been published over the last two decades, demonstrating an increased recognition that farmers' knowledge can offer insight into soil quality, which can guide future research to develop sustainable land use (Barrios and Trejo, 2003). Yet, its use is often limited due to a general lack of understanding of local knowledge and how it can be explored (Oudwater and Martin, 2003), and a subjective sense of inequity between formal science and farmers' knowledge (Ellen et al., 2001).

Local soil knowledge has been defined as "the knowledge of soil properties and management possessed by people living in a particular environment for some period of time" (WinklerPrins, 1999). Many studies have compared local farmers' perceptions of soil fertility and/or perception of soil classification with scientifically determined soil properties (Corbeels et al., 2000; Gray and Morant, 2003; Osbahr and Allan, 2003; Mauro, 2003; Birmingham, 2003; Desbiez et al., 2004; Nyombi et al., 2006). Other studies have highlighted the potential of local soil knowledge for sustainable soil management (Roming et al., 1996; Lefroy et al., 2000; Doran, 2002; Ali, 2003; Pulido and Bocco, 2003; Barrios and Trejo, 2003; Ericksen and Ardón, 2003; Barrios et al., 2006). One study examined how farmers assess soil quality (cf. Roming et al., 1995). In general such studies provide good information for particular soils and land management practices. Beyond that, they reveal that a worldwide consensus of standardized soil quality indicators is difficult to achieve because local knowledge is location-specific.

With regard to the production of irrigated rice in the south of Brazil, the relevance of local soil knowledge has not been documented. Rice is the predominant crop in the southern lowlands producing approximately 5,5 million tons of rice per year, equivalent to 52% of total Brazilian rice production (Azambuja et al., 2004). Production levels are high, but there is clear evidence that the threat to soil quality in terms of physical, chemical and biological degradation due to intensive rice production also is high (Müller et al., 2000; Lima et al., 2002; Pedrotti et al., 2005). As a first step in reverting this trend, researchers need to understand what local farmers know about soil quality. However, this information is only valid when the potential use of this knowledge for maintenance of soil quality and the development of sustainable land management is assessed and put in the context of decision-making (Basic et al., 2003; 2006).

The objective of the research presented here was to answer the following questions: (1) What soil quality perceptions do rice farmers have? (2) Which soil quality indicators are the most important for them? (3) Do rice farmers use their local knowledge about soil quality indicators as a tool for guiding soil management decisions and development of sustainable land management?

2.2. Study Area

The community of our study was "Banhado do Colégio", which is located in the municipality of Camaquã (between latitude 30º48' and 31º32' S, and longitude 51º47' and 52º19'W, see Figure 1, Chapter 1); in the state of Rio Grande do Sul, southern Brazil.

The area of the study was selected because the farmers use the main irrigated rice management systems of Rio Grande do Sul namely: semi-direct, pre-germinated and conventional. There is a large variation of farm sizes (2-500 ha) in the region, which was supposed to yield interesting insights. Furthermore, the farmers are acquainted to this type of study as they belong to a land reform settlement. This kind of settlement generally consists of small farmers who are open to changes and are willing to exchange experiences in order to achieve better living (or even survival) conditions. Research by Fernandes (2004) involving small farmers (sometimes called "peasants") revealed reasons why they are an important feature of Brazilian agriculture, especially in the rural reality of the state of Rio Grande do Sul. According to this author, in a broader sense, small farmers have better ability to handle dificulties and achieve high land productivity while having less support and resource than big farmers.

2.2.1. Rice management systems description

The growing period of rice is from sowing between late September and early December up to harvest in March-April. The three main management systems differ with respect to intensity and timing of soil tillage and water use.

(a) Semi-Direct - the soil preparation is done in September or October (around 45-60 days before sowing) when the soil is not inundated. This early soil preparation with a disc plough and disc harrow permits the incorporation of the straw and the germination of the weeds. A herbicide is used to kill these weeds, and rice is sown without seedbed preparation, to avoid regrowth of weeds. Fields are inundated after emergence of the seedlings, as in the case of the conventional system.

(b) Conventional - just before the sowing period, the fields for rice are prepared when the soil is not inundated. This is done by deep tillage with a disc plough followed by superficial operations with a disc harrow with the aim to level the soil and prepare a seedbed of fine aggregates. Sowing (drilling) is done on with a conventional sowing machine. Water is let on the field after the seedlings have reached a height of approx. 10 cm.

(c) Pre-germinated - the field is inundated (early August) before the tillage operations start. Tillage is done in September and October. Usually, the same disked implements are used as in the conventional system, often complemented with a pass of a special leveller to smoothen and level the puddled surface layer. Seeds are pre-germinated by soaking until the coleoptile is 2-3 mm. Seeds are broadcast in the shallow (5-10 cm) water layer either by hand or sowing machine, depending on the size of the farm. The water layer allows a more precise levelling of the field and controls weeds.

A calendar of the three systems and the average monthly rainfall is shown in Table 1.

Table 1. Period of soil tillage and water use operations for the rice management system studied and the mean rainfall for the region

Management System (% of the use of this system in Camaquã, the range of farm size and average rice yield)	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Semi-Direct (65%, 5-200 ha, 5.7 ton ha^{-1})		Fallow/Cattle			Soil preparation[1]		Chemical weed control and sowing [3]				Harvest	
Inundation								XXXXXXXXXX				
Conventional (25%, 200-500 ha, 8.4 ton ha^{-1})	Fallow/Cattle				Soil preparation[1]		Sowing[3]				Harvest	
Inundation								XXXXXXXXXXXX				
Pre-germinated (10%, 2-30 ha, 6.3 ton ha^{-1})	Fallow/Cattle			Soil preparation [2]		Sowing [3]					Harvest	
Inundation				XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX								
Mean rainfall (mm)	56	108	92	136	113	125	157	94	172	172	82	120

[1] Plough and harrow

[2] Plough, harrow and leveler

[3] Drained field is required for sowing operation. Pre-germinated seeds are used in the pre-germinated management system

2.2.2. Community history

The community of Banhado do Colégio started during the first Brazilian land reform in 1959. When the community was founded in the early sixties, the area was a swamp, which was drained, and approximately 200 families started farming. The lots (10 – 25 ha each) were gradually distributed to landless family farmers. These families were mainly descendants of German and Polish settlers who immigrated to Brazil in the end of the 19th century (Westphal, 1998; Ferreira, 2001). The soil was very fertile and one of richest in organic matter in Brazil. The predominant soil types are Albaqualfs and Humaquepts (Soil Survey Staff, 2006). The main difference between these soils is the clay content in the topsoil (Cunha et al., 2001). Some topsoil (0-10 cm) properties for the two soil great groups from the study area are presented in Table 2.

Table 2. Mean values of some topsoil (0-10 cm) properties for the two soil great groups studied in Camaquã region (values applied for after the harvest)

Soil Great Group	Colour	Organic Matter (%)	Clay (%)	Ph (1:1)	Bulk Density (g cm^{-3})	Total Porosity (%)	Total N (%)	P (mg dm^{-3})	K (mg dm^{-3})
Albaqualfs	White	2.6	26.5	4.9	1.5	0.4	0.1	8.4	36.0
Humaquepts	Black	7.7	59.8	5.0	0.9	0.6	0.5	10.8	41.6

The total area of the community is 4900 ha, mostly characterized by fields that are not very suitable for crops other than irrigated rice. Indeed, rice production was started soon after the start of the community, pushed by rural extension services. The inherent fertility of the soils was also a reason to attract farmers to the new community, although they hardly had any experience in growing rice.

Since then, the same fields are still used for agricultural production, but with an increased use of external inputs (seeds, pesticides, fertilizers, etc), and increased intensification in soil preparation and use of water (Cunha et al., 2001). As a result, the rice production level can reach records of 9 ton/ha.

Not all original farmers and their descendants are better off today than when the community was created. About one third of the original farmers and their descendants no longer live in the community. Of those still living in the community, the majority (small farmers) has difficulty earning a reasonable living and economically depends on the production of rice or on their pensions. A few, however, have prospered by producing rice in larger areas. They have good infrastructure, such as farm storage facilities, machinery and are better positioned to obtain financial support from banks than small farmers. These farmers bought neighboring lots and now possess large farms using conventional or semi-direct rice management systems. The majority of the small farmers use the pre-germinated rice system mainly because of lower costs, easier weed control and less dependence on the weather for soil preparation and sowing activities. The natural and efficient weed control by the intense use of water in pre-germinated systems gives enables of rice production year after year. Thus, the choice of pre-germinated systems, specifically by these small farmers, is of fundamental importance because of the limited availability of agricultural areas. Besides, these areas are generally located in lowland fields where a rotation of rice with soybean is not profitable.

2.3. Methodology

2.3.1. Study design

Semi-structured interviews alternated with discussion groups were chosen as research methods in order to accurately assess farmers' knowledge at the individual and group level and to identify if differences in soil quality perception occur between farmers who use different management systems (for further explanations of this methodological rationale see Bernard, 2002). All interviews and discussions were recorded on tape for analysis.

2.3.1.1. Initial individual interviews

Semi-structured interviews were used for gathering information on perceptions of soil quality indicators. These interviews took place at the farmer's house or in his/her field. Out of the 200 active rice farmers, 50 were chosen to be interviewed based on the following criteria: (a) farmers should own and work the fields themselves in order to minimize misunderstandings due to limited knowledge of the soil or the management systems; and (b) the three management systems had to be represented. After contacting those potential farmers, only 32 of them were interviewed (3 using conventional management system, 13 using pre-germinated system, and 16 using semi-direct system, Table 3) because not all farmers were ready to spend the necessary time or were not interested in a participation in the study. This first round of individual interviews was held in November and December 2003. The farmers were presented to two open and broad questions: *"What do you think is a good soil?"* and

"How do you recognize a good soil?" This resulted in an inventory of farmers' perceptions of soil quality and of the soil quality indicators that they use.

Table 3. Descriptions of farmers' name, management systems, soil colour and the size of their fields

	Pre-Germinated		Semi-Direct		Conventional	
Soil Colour	Farmer	ha	Farmer	ha	Farmer	ha
Black	Celso[2]	4.5	Nilso	6.0		
	Valdir	19.0	Jaime	12.0		
	Helio	3.0	Vilmar	12.7		
	Albino	11.0	Antonio Bartz[2]	12.0		
	Orzeli[2]	30.0	Luis	6.0		
	Carlos	10.0	Plinio	20.0		
	Iduino	17.0	Antonio Nunes	10.0		
	Antonio Bartz[2]	4.0	Reinaldo	18.0		
			Aderaldo	49.0		
			Antonio Neto	12.7		
			Neuza	47.7		
Mix	Antonio Neuman	12.5	Bruno	16.0		
	Darci	14.0	Adelino	6.0		
	Evaldo	18.0				
White	Flavio	23.0	Álvaro[2]	7.5	Raul	350.0
	Ermenegildo	5.4	Nilton[1,2]	20.0	Mario/Adolfo[1,2,3]	210.0
			Lucidio[2]	5.0	Hugo	380.0

[1] Farmers who have field in black and white soils
[2] Farmers who have fields under semi-direct and pre-germinated systems
[3] Farmers who have fields under the three management systems

2.3.1.2. Discussion group meeting

A discussion group meeting was held in January 2004. Out of the 32 farmers who participated in the individual interviews, 18 farmers responded to the invitation (1 using the conventional management system, 9 using the pre-germinated system, and 8 using the semi-direct system). First, participants were divided into three groups to start a discussion of the list of soil quality indicators that emerged from the individual interviews. This step served as a warming up and to acquaint the farmers with the topic of soil quality. Next, the whole group was brought together for a final discussion. During this meeting farmers were given several opportunities to discuss their own perceptions of soil quality indicators. The main purpose of this meeting was to rank the list of soil quality indicators collected from the individual interviews and to reach consensus about the most important indicators. Two facilitators were involved in guiding and documenting the discussion. The meeting lasted three hours.

2.3.1.3. Further individual interviews

For the third objective (“do farmers use their knowledge on soil quality?”), we interviewed 24 farmers from the original group of 32, in June/July 2005. The other farmers were unable to be interviewed. However, all three management systems were represented in the sample (2 farmers using the conventional management system, 8 farmers using the pre-germinated system, and 14 farmers using the semi-direct system). The following open questions were asked: *“Do you use soil quality indicators in your day-to-day decisions?*” If so, *“Which is the most important indicator for guiding soil management decisions?”* and *“Why, when and how do you use it?”*

2.4. Results

2.4.1. Rice farmers’ perceptions of soil quality

The rice farmers of Camaquã region distinguished soil quality primarily on the basis of three classes of soil colour: black (*preto*), mixed (*misturado*) and white (*branco*). They considered the colour of the soil as a proxy for soil quality. According to their perception black soil is found in lower areas and is the best soil because it contains more clay, is rich in organic matter, is softer, has better infiltration, is more fertile, has more soil organisms and nutrients, and thus produces more. During the interview, each farmer valued his/her own lot by using terms as “good”, “rich” or “strong” for black soils, “moderate” for mixed soils and “bad”, “poor” or “weak” for white soils.

The perception of soil quality was not only closely related to environmental factors but also to economic factors. The farmers emphasized that a good soil has to be flat (level) and low-lying because this saves costs for soil preparation and water management of the irrigated rice. This view is supported by the fact that lower areas are more expensive to buy or rent.

The farmers frequently addressed properties of the topsoil rather than subsoil features to assess whether the soil was recovering from previous cropping. This is probably because topsoil is influenced more by tillage and plant growth than subsoil and also because they rarely see the subsoil.

Farmers also pointed to visual features while walking in the field (e.g., spontaneous vegetation, soil colour). Many indicators related to rice plant performance (e.g., yield, rice plant and root development) were mentioned as soil quality indicators. Most farmers also touch and feel the soil for assessment of the quality (rubbing soils between fingers to feel its quality), as stated by a farmer:

> *"Soil is like cloth: we really see what is good when we touch it"* (Hélio Duarte).

In the initial individual interviews, 11 soil quality indicators were mentioned. Indicators were considered greater in importance if they were mentioned by more farmers. The list and classification of the farmers' soil quality indicators are shown in Table 4.

Table 4. List and classification of the farmers' soil quality indicators

Indicator	% of farmers who mentioned the indicator	Farmers' statements
Biological		
Earthworms	97	"Where there is strong soil we can find earthworms"
Physical		
Friability	43	"A soft soil better allows the development of the roots" "We can feel if the soil is hard or not by just walking"
Chemical		
Organic matter	57	"A good soil is a black soil, which has more fat (organic matter) in it" "If the soil has fat it means a stronger soil, with more nutrients, so it is more fertile."
Plant Performance		
Yield	67	"Good soil is one which produces a lot"
Spontaneous vegetation	63	"Good soil can be seen through its own vegetation. It has to be strong, vigorous, well developed, have beautiful green colour, fast growth." "If there is vegetation, any crop can grow on that field"
Root development	53	"A plant that has more roots finds more food (nutrients)" "If a soil permits the growth of the root, this means a soft soil" "Short root: low yield"
Rice plant development	43	"The quality of a soil can be seen during the rice plant development"
Rice plant colour	16	"The gold yellow of the rice flower and the dark green of the rice plant tell us that the soil is good, so the colour of the rice plant can give us the information about how the soil is"
Number of rice tillers	16	"The higher the number of rice tillers, the better the soil"
Intrinsic soil characteristics		
Soil colour	87	"The blacker the soil, the better soil quality"
Other		
Healthy and good-looking cattle	10	"If a field has beautiful cattle (fat), it means strong natural vegetation from a good soil"

Out of the 11 soil quality indicators mentioned only soil colour, earthworms, soil organic matter and soil friability were unanimously considered by farmers as significant indicators of soil quality, with soil colour as the most important one. They could not decide on the order of importance of these four indicators because they assume that all are related. According to farmers' comments if the soil is darker, it will contain more clay, a higher percentage of organic matter, more and stronger spontaneous vegetation, more earthworms and other organisms and, consequently, higher soil friability, better root development and higher yields.

2.4.2. Local soil knowledge and soil management

The second round of individual interviews showed that three indicators were found to be useful and important in decision-making: spontaneous vegetation, rice plant development and soil colour. Additionally, the usefulness depends on the management system used, and the type of decision to be made, i.e, day-to-day management or buying and renting decisions.

2.4.2.1. Spontaneous vegetation

For farmers who applied semi-direct and conventional management systems, the appearance of spontaneous vegetation during the fallow period was the most important soil quality indicator, because the soil can get "natural benefits" from the vegetation. More spontaneous vegetation results in a reduced use of artificial fertilizer because the biomass is considered a natural organic fertilizer. Besides, the farmers believe that the decomposing vegetation increases the "fat" of the soil (organic matter), maintains soil friability and soil water content, promotes earthworms and microorganisms, and can protect against erosion.

Looking at the appearance of spontaneous vegetation farmers can decide whether or not to apply supplemental fertilization (usually based on nitrogen) or postpone this action till the next annual cropping season based on soil chemical analysis. According to the farmers, if the spontaneous vegetation displays a dark green colour and shows good development of the plants in terms of height, they assume that their fields are good for the following crop and there is no need to verify by soil chemical analysis if additional fertilization is necessary. Thus, spontaneous vegetation is considered to contribute to soil quality and, consequently, to sustainability of farming. As commented by a farmer in the second round of individual interviews:

> *"If a field can always sustain much spontaneous vegetation during the fallow period it means that the soil is going to keep its own life for my grandchildren"* (Reinaldo Zaikowisk).

A second farmer added:

> *"The soil health of tomorrow is like the health of a person; it depends on today's eating habits"* (Adolfo Westphal).

2.4.2.2. Rice plant development

Farmers who practice the pre-germinated system cannot evaluate the quality of their soils looking at the spontaneous vegetation during the fallow period because their soils are too degraded (by the fact that the soil 'fat' is lost by soil preparation) to support much spontaneous plant growth and also because the fallow is shorter (they start to prepare the soil earlier). So, these farmers have no idea of their soil quality before preparing the soil and planting rice. Soil quality is only assessed by observing rice plant development in terms of colour, height, root development and numbers of tillers.

2.4.2.3. Soil colour

When farmers want to buy or rent land, this indicator is the most important. They assume that black soil has a higher economic value and will have a high potential production because of the benefits (qualities) mentioned earlier.

2.4.3. The use of local soil knowledge in land management

The farmers are conscious of the fact that soil quality varies from field to field because of inherent soil characteristics and the strong influence of management practices. Farmers are also aware of soil degradation and its association with land management. Much of the soil degradation in the region is observed in the pre-germinated management system. Farmers revealed to be conscious that long periods of inundation could damage the soil because it becomes much more acid, promotes iron toxicity, increases compaction and reduces soil life.

Farmers believe that rotation of irrigated rice with soybean increases soil fertility, "softens" the soil and results in a better control of weeds[1]. Fallowing and cattle grazing for 2-3 years is another option to improve soil quality. Farmers used to say that the grazing cattle

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[1] = red and black rice; other spontaneous vegetation is not considered weeds.

add manure to the field, crop residues add organic matter to the soil and roots that remain in the field retain soil moisture. As a result, the soil life is diversified.

However, they consider that these options are limited to only a small part of the farmers, those who have more land or money. The majority of these farmers automatically adopt the conventional system and some of them use the semi-direct system. They do not depend on just one piece of land for his/her survival; they can divide their land in order to produce rice, soybean or keep a field under fallow.

2.5. Discussion and Conclusions

Although farmers described their own soils as sandy and clayey, they mainly classify the soil quality according to soil colour. Farmers relate soil colour to soil fertility (organic matter) and consequently to quality. The use of colour as a major descriptor of soils has also been reported by Saito et al. (2006) from northern Laos by different ethnic groups. Rice farmers in Laos preferred black soils to red, white and yellow soils, and preferred clayey or loamy soils to sandy or stony soil. Darker soils were considered to contain high levels of organic matter, to have a high water-holding capacity, to be inhabited by earthworms and to produce high rice yields and were commonly considered more fertile than soils of other colours. This was also the case in our study: black soil (*terra preta*) was considered the most fertile because of its high clay and organic matter content, whereas white soil (*terra branca*) was considered the least fertile because of its low clay and organic matter content. A comparison of these local farmers' responses with the formal values presented in Table 2 support farmers' understanding of soil quality. Similar findings (Roming et al., 1996; Coorbeels, et a., 2000; Barrios and Trejo, 2003; Ali, 2003; Desbiez et al., 2004) show that soil colour is the most widely used indicator for classifying soils in other parts of the world and different crops as well.

The interviews showed that farmers have a holistic view of soil. Farmers see soil quality as a dynamic asset, integrating the chemical, physical and biological characteristics. As a farmer commented:

> *"I cannot separate what happens in the soil…for me everything is related…it is alive…it is a living system…and the things happen in cycles."* (Bruno Ritter).

The Camaquã farmers are interested in soil productivity and appropriate management practices. Their emphasis tends to be that a good soil is a 'productive' soil. They associate good soils with productive crops, as was also found by Bruyn and Abbey (2003). However, it was admitted that the relationship between yield (a measurement of soil productivity) and soil quality is complex. As farmers said:

"Yield does not indicate a good soil. Any well-treated soil produces!" (Antônio Bartz).

"The yield depends on the weather rather than other factors" (Adelino Oswaldt).

These statements reveal that in the eyes of the farmers yield does not indicate good soil because they know they can manipulate their soils to get high yields. Thus, some of the potential indicators those farmers would use as 'natural' indicators of soil quality, they could not use nowadays because of the intensive use of external inputs and/or modified seeds.

2.5.1. Small vs. big farmers

Two main farmer groups exist in the region: small and big farmers. They are mixed up in the regional landscape. Local soil knowledge is not related to the size of the farms, but the opportunities to use it are farm-size related. Farmers pointed out that soil quality could be changed through time because soil fertility can be manipulated. Potentially, for small farmers rice rotation with soybean or fallowing could improve their soils' quality and might raise additional income just as in the case of big farmers. However, small farmers (mainly those who use the pre-germinated rice management system) cannot risk their own sustenance by using soybean instead of rice because their low land is likely to flood during the growing season, which is fatal for soybeans. The risk of flooding in the small farms is also related to the water management systems of their neighbours (when these grow rice). Furthermore, agrochemical (such as herbicide) applications by the neighbours can damage their crops. Large farmers (who mainly use the conventional and in some cases semi-direct rice management systems), on the other hand, can plant soybean because they possess larger and higher-lying pieces of land, and have better infrastructure for drainage and, therefore, are less vulnerable to weather extremes and are hardly affected by their neighbours' land management.

Hence, as also was shown in a study by Scoones and Toulmin (1998) socio-economic issues are key driving forces of day-to-day and long-term decisions about specific practices, such as rice-soybean rotation, the irrigation system, the use of fertilizer, the rice varieties and the machines to till the soil. This can be illustrated by the following farmer's statement:

> *"We already know our lands very well…we do not have surprises after all…we know that sometimes we are doing something wrong but it is not because we do not have knowledge, it is because we do not have economic resources to do the right thing"* (Ederaldo Dumer).

This result is in contrast with some other local soil knowledge studies, such as for example on farmers from Central Honduras, where Ericksen and Ardón (2003) found that the farmers prefer, as a primary solution, to apply more fertilizer instead of managing the soil with soybean rotation or fallowing to recuperate soil quality.

2.5.2. Farmers' local and scientists' formal knowledge

The responses of farmers to questions showed that to them the concept of soil quality is complex with no single indicator making a soil good or bad. Organic matter is something most farmers acknowledge as an essential indicator. They know that it comes from decomposing crops, which supply what the soil "needs" and correct what is "missing" (nutrients). Contrary to the study of Barrios and Trejo (2003), the farmers in this study did not distinguish between types of vegetation growing on their soil. Barrios and Trejo (2003) provide lists of native plants as important local soil quality indicators associated with modifiable soil properties from different regions of Latin America. They showed that traditional farmers use associations of native plants as indicators of soil quality, and native plants as indicators of locations where crops should not be grown. In our case, farmers were more interested to know if any vegetation grows vigorously or not. They do not investigate the relationship between different natural vegetations and regional soil fertility, although this might help them in taking management decisions.

Farmers of Camaquã know that organic matter can be influenced by land management practices. One farmer who uses the pre-germinated system explained:

"*Because we prepare the soil under water our soils are too much washed (impoverished)…all fat (organic matter) of the soil goes out from the fields to the drainage channels"* (Álvaro Bueno).

However, they do not have quantitative information and, therefore, cannot be certain about the effectiveness of the measures they take.

Another factor to be considered is that farmers in this study generally only take the topsoil or the tilled layer into account. Thus, their perceptions rely on soil indicators that they can see and/or experience there. Farmers' interpretations then are not necessarily based on sufficient information because of their limited observations. For example, although the majority of farmers (97%) identified earthworms as a good soil quality indicator, the presence or absence of earthworms in the soil was not important in the farmers' decision making. A possible explanation is that they hardly see earthworms in their own fields because of the effects of management systems, particularly tillage, water management and pesticide use. Farmers said:

"*As our lands are under the water during the most of time, so there is no time for the earthworm to appear…besides, the earthworm does not like inundated soil…they cannot survive on that"* (Orzeli Reinard)., or

"Because of the herbicides the soil is dead!" (Antônio Kila Neto).

Earthworm species that may occur in deeper layers or semi-aquatic earthworms did not concern the regional farmers. From the scientist's point of view the farmers then do not use an indicator, which they consider important, to its full potential. On the other hand, scientists often underestimate the importance of socio-economic factors in farmers' management decisions.

Rice farmers from Camaquã showed to have detailed knowledge of the soil they are cultivating. The holistic farmers' view of soil quality is based on dynamic processes integrating chemical, physical and biological soil characteristics. They know what indicates the quality of their soil, but nowadays they can hardly use these indicators due to limitations set by their management practices. Nevertheless, conventional and semi-direct management systems (larger farms) better allow application of farmers' knowledge than the pre-germinated management system (small farms). Our results provide a better understanding of the importance of farmer's knowledge of soil to the sustainability of farming systems.

Researchers must continue to face the challenge to provide a base for bridge-building between the best (largely holistic) farmers' and (largely reductionist) scientists' knowledge. In so doing, they will help to develop mutually acceptable indicators of soil quality (Roming et al., 1995; 1996) for sustainable land management.

Farmers are the principal actors in agriculture, and their knowledge should be considered one of the most important assets in striving towards sustainability. Therefore, an important role for scientists in formal soil quality research is to strengthen the capacity of farmers to make informed management decisions and to evaluate the feasibility of alternative production systems in terms of long-term soil quality. Our study shows that this is particularly true in the rice production systems under investigation.

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Chapter 3

Soil quality assessment in rice production systems: establishing a minimum data set

Abstract

Soil quality, as a measure of the soil's capacity to function, can be assessed by indicators based on physical, chemical and biological properties. Here on we report the assessment of soil quality in 21 rice (*Oryza sativa*) fields under three rice production systems (semi-direct, pre-germinated and conventional) on four soil textural classes in the Camaquã region of Rio Grande do Sul, Brazil. The objectives of our study were: (i) to identify soil quality indicators that discriminate both management systems and soil textural classes, (ii) to establish a minimum data set of soil quality indicators and (iii) to test whether this minimum data set is correlated with yield. Twenty-nine soil biological, chemical and physical properties were evaluated to characterize regional soil quality. Soil quality assessment was based on factor and discriminant analysis. Bulk density, available water and micronutrients (Cu, Zn and Mn) were the most powerful soil properties in distinguishing among different soil textural classes. Organic matter, earthworms, micronutrients (Cu, and Mn) and mean weight diameter were the most powerful soil properties in assessing differences in soil quality among the rice management systems. Manganese was the property most strongly correlated with yield (adjusted $r^2 = 0.365$, $P = 0.001$). The merits of sub-dividing samples according to texture and the linkage between soil quality indicators, soil functioning, plant performance and soil management options are discussed in particular.

Keywords: Soil quality indicators; minimum data set; rice; Brazil.

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3.1. Introduction

In the state of Rio Grande do Sul, Brazil, rice (*Oryza sativa*) production is one of the most important regional activities. Rice production is located mainly in the southern lowlands where approximately 5.5 million tons of rice per year are produced, equivalent to 52% of total Brazilian rice production (Azambuja et al., 2004). The inherent fertility of the region has led to expansion of rice cropping and an increase of land use intensity, mainly in the Camaquã region, over the last half century (Westphal, 1998; Cunha et al., 2001). There is a growing concern with farmers that the land use practices in the Camaquã region may not be sustainable because of their detrimental effects on soil quality.

The most commonly used definition of soil quality is: "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" (Karlen et al., 1997). This capacity of the soil to function can be assessed by physical, chemical and/or biological properties, which in this context are known as soil quality indicators (Wander and Bollero, 1999). Perceptions of what constitutes a good soil vary. They depend on individual priorities with respect to soil function, intended land use and interest of the observer (Doran and Parkin, 1994, Shukla et al., 2006). Soil quality changes with time can indicate whether the soil condition is sustainable or not (Arshad and Martin, 2002, Doran, 2002). Maintaining soil quality at a desirable level is a very complex issue due to climatic, soil, plant, and human factors and their interactions and it is especially challenging in lowland rice cropping systems because of puddling practices in soil preparation (Chaudhury et al., 2005). Although the concept of soil quality is often advocated (Karlen et al., 2001), it is also criticized in the literature because of "its premature acceptance and institutionalisation of an incompletely formulated and largely untested paradigm" (Sojka and Upchurch, 1999).

Minimum data sets of soil quality indicators have been proposed for plot and field scales (Doran and Parkin, 1996), regional scales (Brejda et al., 2000a,b) and for national scales (Sparling and Schipper, 2002; Sparling and Schipper 2004; Sparling et al., 2004). However, there is currently no consensus on a definitive set of soil properties for soil quality monitoring, nor consensus on how the indicators should be interpreted (Schipper and Sparling, 2000). This lack of consensus is partly due to the fact that soil quality is a complex concept and that different site-specific soil conditions may be desirable, depending on the purpose of land use.

The assessment of soil quality can be viewed as a primary indicator of the sustainability of land management (Doran, 2002). Basically, two types of approach are employed for evaluating the sustainability of a management system: (i) comparative assessment and (ii) dynamic assessment (Larson and Pierce, 1994). The comparative approach has frequently been used and has shown that multivariate statistical analyses are useful tools to identify indicators and to interpret correlations of indicators (e.g. Wander and Bollero, 1999; Brejda et al, 2000a,b; Govaerts et al, 2006; Shukla et al., 2006). These studies are based on different land uses in a single dominant soil group (Brejda et al., 2000a) or in different soil great groups (Brejda et al., 2000b; Schipper and Sparling. 2000; Sparling and Shipper. 2002) or based on the same land use under different management systems (Chaudhury et al., 2004; Govaerts et al., 2006). Our study relates to one land use (rice production) under three different management systems, on two soil types, suggesting that multivariate analyses of sample data would be appropriate in this case.

To make the results of our study useful for dynamic assessment of soil quality, we used a novel approach. Farmers in the study area mainly evaluate the production potential of the soils according to texture. We sub-divided the samples into 4 textural classes according to clay and therefore focus the study on those soil quality indicators that are interpretable by farmers. Our approach establishes a minimum data set of soil quality indicators which is able to show not only human effects (as a result of management systems applied by farmers), but also differences due to inherent soil characteristics (soil texture classes). We also analyzed a larger pool of soil properties than is commonly the case.

The study was conducted with the following objectives: (i) to identify soil quality indicators that discriminate both management systems and soil textural classes, (ii) to establish a minimum data set of soil quality indicators and (iii) to test whether this minimum data set is correlated with yield.

3.2. Material and Methods

3.2.1. Area description and soil sampling

Camaquã is located in the south of Brazil, in the Rio Grande do Sul state, between latitude 30º48’ and 31º32’ S, and longitude 51º47’ and 52º19’W (see Figure 1, Chapter 1). Mean annual rainfall is 1213 mm and the average temperature is 18.8ºC (Cunha et al., 2001).

Albaqualf and Humaquepts (Soil Survey Staff, 2006) are the two soil great groups found in this region. One of the major differentiating factors between and within these soil groups is clay (Cunha et al., 2001). We selected the three rice management systems mostly used in the state: conventional, pre-germinated and semi-direct. These systems are different with respect to intensity of soil tillage and water use (see Table 1, Chapter 2).

Twenty-one rice fields on different soil great groups and under different rice management systems were selected. In each field, five replicate plots, 2x2 m each, were randomly laid out within an area of 3 ha. In total 105 representative plots were sampled. From within each sampling area, 20 samples were taken from 0-10 cm depth using a hand spiral, tube auger and shovel. The soil samples were collected immediately after the rice harvest of 2004. These samples were bulked and mixed for the analysis of chemical, microbiological and physical properties. For those analyses requiring intact core samples, we obtained an additional three undisturbed soil cores from each plot. Earthworms were hand-sorted from a 30x30x30 cm monolith, localized in the central area of each plot. In addition to the soil samples, all mature rice plants were manually harvested from each plot area.

3.2.2. Soil analysis

Samples collected for microbiological analysis were placed in a cooler with ice packs for transport to the laboratory. The samples were analyzed for microbial biomass (MB), soil respiration (SR), potentially mineralizable N (PMN), ß-glucosidase (ßG), acid phosphatase (ACP) and alkaline phosphatase (ALP). Microbial biomass was determined using microwave irradiation of soil (Islam and Weil, 1998). Flow-through respirometry was used to measure SR, using an automatic respirometer with a CO_2 analyser (Sable System, Las Vegas, NE, USA). Potentially mineralizable N was measured using the ammonium production during waterlogged incubation (Bundy and Meisinger, 1994). Enzyme activity was measured using spectrophotometer according to Tabatabai (1994). Earthworm number (EN) was assessed using the standard method of the Tropical Soil Biology and Fertility Programme (TSBF) (Anderson and Ingram, 1993).

Chemical analysis was done using the methodology described by Tedesco et al. (1995). Samples were analyzed for organic matter (OM) using the Walkley-Black method, total N (TN) using the Kjeldahl method, pH (1:1, soil:H_2O) and Al saturation (Al sat = 100* (exchangeable Al)/(exchangeable Al + Sum of bases)). Exchangeable Ca, Mg, and Al were extracted by 1M KCl. Ca and Mg were determined by atomic absorption spectrometry and Al by titration with NaOH. Extractable P and exchangeable K were extracted by a Mehlich 1 solution (0.05M H_2SO_4 + 0.05M HCl). P was determined by UV-visible spectrophotometry and K by flame photometry. Potential acidity (PA) was estimated by SMP buffer solution and cation exchange capacity (CEC) as sum of bases + (PA). Micronutrients (Fe, Zn, Cu, Mn) were determined by atomic absorption spectrometry. Mn was extracted by 1M KCl. Zn and Cu by 0.1M HCl and Fe by 0.2M ammonium oxalate at pH 3.0.

Bulk density (BD), texture, water stable aggregates (WSA), microporosity (MiP), and soil water retention on pressure plates at -340 and -1500 kPa were the physical analyses measured according to methods described by Klute (1986). The results from textural analysis (hydrometer method) were used to divide the soils into 4 soil textural classes according to clay content (<20%, 20 - 40%, 40 - 60%, >60%), following the standardized division of textural classes used to diagnose soil fertility in the state of Rio Grande do Sul (Manual, 2004).

Some indicators were calculated from the measured data set: available water (AW = difference between water content at field capacity and permanent wilting point), macroporosity (MaP = difference between total porosity and MiP), mean weight diameter (MWD = Σ (mean diameter x aggregates weight) / sample dry weight)) and microbial quotient (Mq = the ratio of soil microbial biomass carbon to soil total organic carbon). These indicators have been suggested as useful for soil quality monitoring (Doran and Parkin, 1994; Schipper and Sparling, 2000).

Grain was collected (before soil sampling) and manually separated from the straw, weighed and moisture content was determined. The final yield was calculated based on 13% moisture.

3.2.3. Statistical analysis

Multivariate statistical analysis of the soil properties was conducted using factor analysis and discriminant analysis. Factor analysis was used to group the 29 soil properties into statistical factors (or principal components) to reduce the entire data set for subsequent discriminant analysis. Principal component analysis was used as the method of factor extraction and factors were subjected to varimax rotation. The general principles of principal component and factor analyses can be found in Webster and Oliver (1990) and guidance for summarizing data is provided by Webster (2001).

Stepwise discriminant analysis was used to select the component(s) that best discriminated among the different management systems and also among the different soil textural classes. Following selection of the best discriminating component(s), soil quality properties that comprised these components were also subjected to stepwise discriminant analysis to select the best set of properties for forming the discriminant functions. Discriminant analysis, therefore, proceeds with the derivation of the discriminant function and the determination whether a statistically significant function can be derived to separate the two or more groups (in our case the three rice management systems and the four soil textural classes).

Holdout method was employed as a technique to validate the results of discriminant analysis. For the methodological rationale related to the factor and discriminant analyses see also Sharma (1996) and Hair et al, (1998). All statistical analyses were conducted with SPSS 11.0 software (SPSS, 1998).

3.3. Results

Significant correlation ($P<0.01$) was observed between 232 of 406 soil property pairs for the Camaquã samples (Table 2). Strongest positive correlations ($r>0.90$) were observed for OM with TN, Ca, MiP and CEC, and for CEC with Ca, PA and MiP. Strongest negative correlations ($r>0.90$) were observed for BD with OM, TN, Ca, MiP and CEC.

Table 2. Correlations among 29 physical chemical and biological soil properties (*n* = 105)

	EN	ACP	ALP	ßG	PMN	SR	MB	Mq	pH	OM	TN	P	K	Ca	Mg	Al	Cu	Zn	Fe	Mn	PA	Al sat	BD	MiP	MaP	AW	WSA	MWD	CEC
EN	1.00																												
ACP	0.00	1.00																											
ALP	-0.13	0.72**	1.00																										
ßG	-0.11	0.77**	0.75**	1.00																									
PMN	0.06	0.54**	0.57**	0.56**	1.00																								
SR	0.08	0.62**	0.54**	0.61**	0.66**	1.00																							
MB	0.03	0.44**	0.69**	0.58**	0.63**	0.59**	1.00																						
Mq	0.04	-0.24*	-0.04	-0.12	0.03	-0.04	0.49**	1.00																					
pH	0.07	0.05	-0.11	-0.17	0.25*	0.20*	0.08	0.19	1.00																				
OM	0.02	0.81**	0.82**	0.81**	0.68**	0.77**	0.62**	-0.25*	0.00	1.00																			
TN	-0.01	0.71**	0.84**	0.78**	0.64**	0.73**	0.70**	-0.14	-0.04	0.95**	1.00																		
P	0.18	0.09	-0.12	0.01	0.20*	0.25**	0.05	-0.01	0.58**	0.10	0.12	1.00																	
K	-0.11	0.22*	-0.01	0.16	0.20*	0.15	-0.11	-0.45**	0.14	0.15	0.09	0.29**	1.00																
Ca	-0.01	0.83**	0.76**	0.80**	0.71**	0.77**	0.60**	-0.18	0.17	0.94**	0.87**	0.14	0.25*	1.00															
Mg	0.04	0.77**	0.53**	0.62	0.56**	0.64**	0.36**	-0.29**	0.21*	0.75**	0.62**	0.17	0.43**	0.85**	1.00														
Al	-0.09	0.26**	0.53**	0.53**	0.22*	0.33**	0.48**	-0.04	-0.48**	0.56**	0.68**	-0.04	-0.08	0.38**	0.19	1.00													
Cu	-0.24*	0.02	-0.23*	-0.01	-0.07	-0.17	-0.31**	-0.18	-0.08	-0.19	-0.30**	-0.21*	0.48**	-0.04	0.14	-0.19*	1.00												
Zn	-0.10	0.47**	0.17	0.40**	0.46**	0.39**	0.15	-0.13	0.27**	0.34**	0.25*	0.24*	0.59**	0.53**	0.61**	0.01	0.65**	1.00											
Fe	-0.11	0.67**	0.59**	0.65**	0.53**	0.59**	0.40**	-0.20*	0.10	0.74**	0.65**	0.14	0.41**	0.81**	0.75**	0.29**	0.18	0.61**	1.00										
Mn	-0.10	0.26**	0.05	0.22*	0.05	0.02	-0.21*	-0.47**	-0.29**	0.16	0.05	-0.13	0.60**	0.16	0.43**	0.15	0.49**	0.40**	0.24*	1.00									
PA	0.01	0.66**	0.73**	0.74**	0.49**	0.58**	0.54**	-0.22*	-0.21**	0.85**	0.83**	0.01	0.10	0.76**	0.63**	0.71**	-0.20*	0.23*	0.58**	0.29**	1.00								
Al sat	-0.08	-0.44**	-0.16	-0.23*	-0.43**	-0.38**	-0.10	0.14	-0.64**	-0.29**	-0.14	-0.27**	-0.36**	-0.49**	-0.56**	0.51**	-0.18	-0.49**	-0.38**	-0.11	-0.06	1.00							
BD	0.06	-0.82**	-0.80**	-0.83**	-0.65**	-0.73**	-0.58**	0.24*	0.00	-0.95**	-0.93**	-0.13	-0.28**	-0.92**	-0.77**	-0.58**	0.07	-0.46**	-0.75**	-0.27**	-0.82**	0.27**	1.00						
MiP	-0.05	0.83**	0.75**	0.79**	0.66**	0.74**	0.55**	-0.26**	0.11	0.92**	0.88**	0.22*	0.31**	0.93**	0.81**	0.50**	-0.05	0.52**	0.77**	0.28**	0.80**	-0.37**	-0.95**	1.00					
MaP	-0.03	-0.06	0.12	0.10	-0.09	-0.10	0.02	-0.03	-0.25**	0.02	0.04	-0.27**	-0.02	0.00	-0.05	0.01	-0.06	-0.20*	-0.02	0.01	0.05	0.07	-0.07	-0.15	1.00				
AW	0.14	-0.25**	-0.23*	-0.44**	-0.14	-0.12	-0.22*	0.07	0.11	-0.25**	-0.24*	0.05	-0.27**	-0.29**	-0.25**	-0.27**	-0.25*	-0.31**	-0.31**	-0.22**	-0.27**	0.02	0.33**	-0.32**	0.10	1.00			
WSA	-0.08	0.60**	0.63**	0.66**	0.44**	0.44**	0.42**	-0.22*	0.00	0.66**	0.64**	0.10	0.37**	0.69**	0.58**	0.43**	0.16	0.47**	0.66**	0.22**	0.58**	-0.21*	-0.72**	0.70**	0.09	-0.44**	1.00		
MWD	-0.16	0.61**	0.59**	0.65**	0.48**	0.40**	0.44**	-0.13	0.03	0.57**	0.54**	0.09	0.39**	0.66**	0.58**	0.37**	0.31**	0.65**	0.65**	0.24**	0.48**	-0.25**	-0.67**	0.68**	-0.05	-0.49**	0.84**	1.00	
CEC	0.00	0.77**	0.77**	0.81**	0.61**	0.69**	0.58**	-0.23*	-0.06	0.93**	0.88**	0.07	0.19*	0.91**	0.79**	0.61**	-0.13	0.39**	0.72**	0.29**	0.96**	-0.25**	-0.91**	0.90**	0.03	-0.30**	0.66**	0.59**	1.00

ACP: Acid Phosphatase, ALP: Alkaline Phosphatase, Al sat: Al saturation, AW: Available Water, BD: Bulk Density, CEC: Cation-Exchange Capacity, EN: Earthworm Number, MaP: macroporosity, MiP: Microporosity, MB: Microbial Biomass, Mq: Microbial quotient, MWD: Mean Weight Diameter, OM: Organic Matter, PA: Potential Acidity, PMN: Potentially mineralizable N, SR: Soil Respiration, TN: Total N, WSA: Water Stable Aggregate, ßG: Beta-Glucosidase

*Significant at the 0.05 probability level

** Significant at the 0.01 probability level

3.3.1. Grouping soil quality indicators

The 29 soil quality properties considered in the principal component analysis were grouped into components. The first five principal components had eigenvalues >1 and accounted for 78.2% of the total variance in the entire data set (Table 3) and therefore were retained for interpretation. Communalities estimate the proportion of the variance in each soil property explained by the components. Communalities for the soil properties indicate that the five components explained >95% of the variance in OM and Ca, ≥90% of variance in BD. TN, CEC, MiP, Al and ≥80% of the variance in PA, ALP, ßG, Mg, MB, Cu, Zn, Al sat and pH. However, the five components explained <60% of the variance in AW, EN and MaP (Table 3).

The order by which the principal components were interpreted was determined by the magnitude of their eigenvalues. The first principal component explained 43.8% of the variance (Table 3). It had high positive loadings (≥0.95) of OM (0.97), TN (0.95) and Ca (0.95), and a high negative loading of BD (-0.95). It also had positive loadings of CEC, MiP, PA, ßG, ACP, ALP, SR, Mg, Fe, PMN, MB, WSA, MWD and Al (>0.50). We identified this component as the "*organic matter component*" because all soil properties comprised in this component were significantly correlated ($P<0.01$) with OM (Table 2).

The second principal component explained 9.68% of the variance (Table 3) and was identified as the "*micronutrients component*" because it had the highest positive loading for Cu (0.77) and Zn (0.64). This component also had a positive loading for MWD (0.62) and a negative loading for AW (-0.61). Moderate positive loadings were found for K (0.43) and WSA (0.43), resulting from the significant correlation ($P<0.01$) between K and Cu, Zn, MWD, AW and WSA (Table 2). A moderate negative loading was found for EN (-0.45), resulting from the significant correlation ($P<0.05$) between EN and Cu.

The third principal component was identified as the "*acidity component*". It explained 9.57% of the variance (Table 3) and had a high positive loading for pH (0.73) and a high negative loading for Al sat (-0.87) and Al (-0.76). These soil properties were grouped together because all three were significantly correlated ($P<0.01$; Table 2).

The fourth principal component explained 9.01% of the variance (Table 3). It had the highest positive loading for Mn (0.74); therefore, it was identified as the *"Mn component"*. This component had a moderate loading for K (0.59) resulting from the largest correlation between this property and Mn (0.60, Table 2). It also had a high and a moderate negative loading for Mq (-0.86) and MB (-0.60), respectively (Table 3).

Table 3. Rotated component loadings and communalities of 29 physical, chemical, and biological soil properties on significant principal components (PCs) for rice fields of the Camaquã region

Soil quality properties	Principal component					Communalities
	PC1	PC2	PC3	PC4	PC5	
Organic matter, %	*0.97*	-0.03	-0.02	0.07	0.01	0.96
Bulk Density, g cm^{-3}	*-0.95*	-0.11	0.03	-0.12	-0.02	0.94
Total N, %	*0.95*	-0.06	-0.15	-0.05	0.04	0.94
Ca, cmol$_c$ dm^{-3}	*0.95*	0.11	0.20	0.05	0.03	0.96
Cation-exchange capacity, cmol$_c$ dm^{-3}	*0.94*	0.03	-0.09	0.15	0.00	0.93
Microporosity, %	*0.93*	0.12	0.04	0.15	0.18	0.94
Potential Acidity, cmol$_c$ dm^{-3}	*0.86*	-0.03	-0.29	0.15	-0.01	0.86
Alkaline Phosphatase, µg p-nitrofenol g soil^{-1} h^{-1}	*0.86*	0.06	-0.10	-0.16	-0.22	0.83
ß-Glucosidase, µg p-nitrofenol g soil^{-1} h^{-1}	*0.84*	0.25	-0.09	0.00	-0.10	0.80
Acid Phosphatase, µg p-nitrofenol g soil^{-1} h^{-1}	*0.82*	0.11	0.18	0.16	-0.03	0.75
Soil Respiration, µmol CO_2 h^{-1} g soil^{-1}	*0.78*	-0.07	0.18	-0.06	0.20	0.70
Mg, cmol$_c$ dm^{-3}	*0.76*	0.15	0.32	0.32	0.07	0.83
Fe, mg dm^{-3}	*0.74*	0.31	0.18	0.16	0.06	0.72
Potentially-Mineralizable N, mg NH_4^+ – N g soil^{-1}	*0.70*	0.08	0.28	-0.16	0.14	0.63
Microbial Biomass, µg C g soil^{-1}	*0.69*	0.08	-0.05	*-0.60*	0.03	0.85
Water stable aggregate, %	*0.69*	*0.43*	-0.03	0.09	0.02	0.67
Mean Weight Diameter, mm	*0.62*	*0.62*	0.02	0.02	0.09	0.79
Cu, mg dm^{-3}	-0.21	*0.77*	0.21	0.36	-0.09	0.82
Zn, mg dm^{-3}	0.36	*0.64*	0.39	0.24	0.26	0.82
Available Water, %	-0.26	*-0.61*	0.22	-0.00	-0.13	0.51
Earthworm, number m^{-2}	0.02	*-0.45*	0.08	0.04	0.23	0.26
Al saturation, %	-0.31	-0.05	*-0.87*	-0.13	-0.06	0.88
Al, cmol$_c$ dm^{-3}	*0.56*	0.06	*-0.76*	-0.03	0.08	0.90
pH, 1:1, soil:H_2O	0.02	-0.08	*0.73*	-0.22	*0.47*	0.82
Microbial quotient, %	-0.15	0.08	0.03	*-0.86*	0.03	0.77
Mn, mg dm^{-3}	0.14	0.33	-0.07	*0.74*	-0.08	0.70
K, mg dm^{-3}	0.14	*0.43*	0.26	*0.59*	0.24	0.69
P, mg dm^{-3}	0.11	-0.16	0.24	0.02	*0.78*	0.72
Macroporosity, %	0.05	-0.10	0.03	0.02	*-0.72*	0.53
						Total
Eigenvalue	12.70	2.81	2.78	2.61	1.78	-
% of variance explained	43.80	9.68	9.57	9.01	6.14	78.20

Highly weighted loadings are presented in italic type. These properties were used in the subsequent stepwise discriminant analysis.

The fifth principal component was identified as the "*P component*" because it had the highest positive loading for P (0.78); it also had a moderate positive loading for pH (0.47) and the highest negative loading for MaP (-0.72) (Table 3). These three soil properties were grouped together because the largest correlation of MaP was with P and the largest correlation of P was with pH (Table 2). This component explained 6.14% of variance (Table 3).

3.3.2. Selecting soil quality indicators

3.3.2.1. Soil textural classes

A stepwise discriminant analysis based on the five principal components obtained from the factor analysis showed that only the first discriminant function was significant and explained 99.1% of the total variance. The components "*Organic matter", "Micronutrients"* and *"Mn"* were the most powerful discriminators of the four soil textural classes (Table 4).

Table 4. Summary of stepwise discriminant analysis among soil textural classes

	Discriminant Function		
	1	2	3
Selected PCs †			
Sig.	<0.001	0.324	0.233
Eigenvalue	5.298	0.033	0.014
% of Variance	99.1	0.6	0.3
Canonical correlation coefficient	0.917	0.178	0.119
Variables and Discriminant coefficient			
PC1: *"Organic matter"*	1.317	-0.198	-0.245
PC2: *"Micronutrients"*	0.926	0.840	0.136
PC4: *"Mn"*	0.748	-0.278	0.866
Selected properties ‡			
Sig.	<0.001	<0.001	0.073
Eigenvalue	6.943	0.352	0.073
% of Variance	94.2	4.8	1.0
Canonical correlation coefficient	0.935	0.510	0.260
Variables and Discriminant coefficient			
Cu	-0.553	0.943	-1.068
Zn	0.075	-0.354	1.391
Mn	-0.532	-0.572	-0.207
BD	1.201	-0.518	0.357
AW	0.276	0.901	-0.007

PC: Principal Component, AW: Available Water, BD: Bulk Density

† 61.9% of cross-validated cases corrected classified (Holdout method)

‡ 71.4% of cross-validated cases corrected classified (Holdout method)

A second stepwise discriminant analysis was performed with the soil properties constituting the three components, i.e. "*Organic matter", "Micronutrients"* and *"Mn"*. This resulted in two significant discriminant functions, in which the first one explained 94.2% of the total variance. Although the second discriminant function was also significant, it accounted for only 4.8% of variance and, consequently, it was not used. Only five properties were selected as the most powerful discriminators among soil textural classes. Bulk density, AW, Zn, Cu and Mn were included in the minimum data set as soil quality indicators of textural classes. The first discriminant function (Table 4) resulted in a clear separation among the soil textural classes (Figure 2).

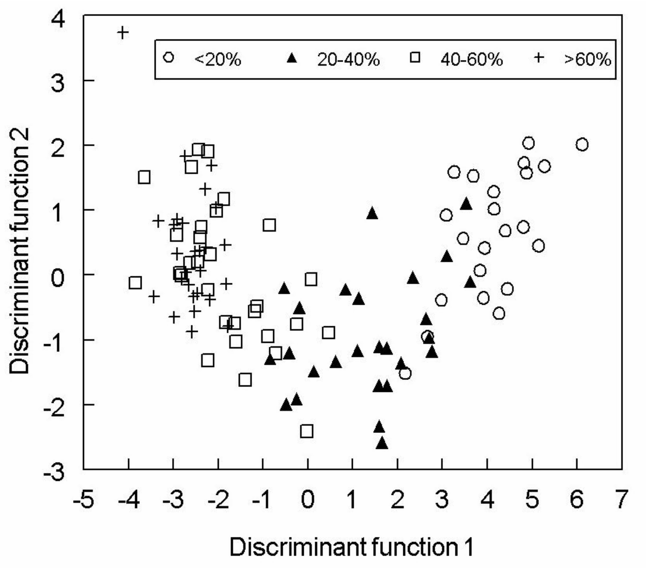

Figure 2. Scores on the two significant discriminant functions based on the highly weighted properties of PC1, PC2 and PC4 in four soil textural classes

3.3.2.2. Management systems

A stepwise discriminant analysis was performed in order to discriminate between the management systems based on the five components obtained from the factor analysis. Two of the discriminant functions were significant and explained 80.4% and 19.6% of the total variance, respectively (Table 5). As was found in the case of the soil textural clases, "*Organic matter*", "*Micronutrients*" and "*Mn*" were also the most powerful components to discriminate between the rice management systems.

Table 5. Summary of stepwise discriminant analysis among management systems

	Discriminant Function	
	1	2
Selected PCs †		
Sig.	<0.001	<0.001
Eigenvalue	1.816	0.444
% of Variance	80.4	19.6
Canonical correlation coefficient	0.803	0.555
Variables and Discriminant coefficient		
PC1: *"Organic matter"*	-0.695	-0.222
PC2: *"Micronutrients"*	0.926	-0.500
PC4: *"Mn"*	0.627	0.779
Selected properties ‡		
Sig.	<0.001	<0.001
Eigenvalue	2.373	1.493
% of Variance	61.4	38.6
Canonical correlation coefficient	0.839	0.774
Variables and Discriminant coefficient		
EN	0.071	-0.476
OM	1.359	-0.494
Cu	0.455	0.729
Mn	-1.368	-0.612
MWD	-0.462	0.862

PC: Principal Component, EN: Earthworm Number, OM: Organic Matter, MWD: Mean Weight Diameter

† 85.7% of cross-validated cases corrected classified (Holdout method)

‡ 88.6% of cross-validated cases corrected classified (Holdout method)

A stepwise discriminant analysis on all the properties comprising these three components produced two significant discriminant functions with 61.4 and 38.6% of the total variance explained, respectively. In total, five soil properties were selected as the most powerful discriminators among management systems. The first discriminant function is a contrast between OM (positive coefficient) and Mn (negative coefficient) (Table 5), which results in a clear separation between the conventional and other management systems (Figure 3).

In the second discriminant function (Table5), no single soil property clearly is the best discriminator among management systems. The five soil properties were highly weighted, without much difference among them. Therefore, all five soil properties result in a clear separation between the pre-germinated and other management systems studied (Figure 3). Mean weight diameter, Cu, Mn, OM, and EN were, therefore, the properties in the minimum data set representing soil quality responses to management systems.

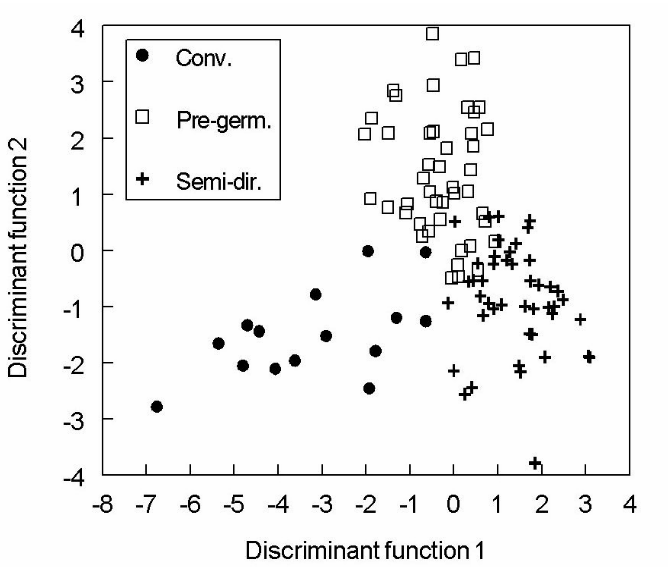

Figure 3. Scores on the two significant discriminant functions based on the highly weighted properties of PC1, PC2 and PC4 in three rice management systems

3.3.3. Yield

In order to investigate whether the soil quality indicators in the minimum data set are correlated with rice yield, a regression was carried out with rice yield as dependent variable and the 8 soil properties as independent variables (adjusted $r^2 = 0.365$). The results (Table 6) show that only Mn significantly predicts yield ($P<0.001$).

Table 6. Results of the regression between the indicators retained in the minimum data set and rice yield

Indicators	Unstandardized Coefficients		t (df=101)
	ß	Std. Error	
(Constant)	869.677	2997.336	0.290
AW	-2670.344	5910.211	-0.452
BD	2376.001	1593.792	1.491
Cu	-495.514	361.409	-1.371
EN	-1.058	0.794	-1.332
Mn	29.697	4.140	7.174***
MWD	-54.841	168.051	-0.326
OM	214.443	143.916	1.490
Zn	86.629	121.362	0.714

AW: Available Water, BD: Bulk Density, EN: Earthworm Number, MWD: Mean Weight Diameter, OM: Organic Matter
Independent Variable: Yield (kg ha^{-1})
*** Significant at the 0.001 probability level

3.4. Discussion

We found the same set of components "*Organic matter", "Micronutrients"* and *"Mn"* to be the most important principal components discriminating among both management systems and textural classes. However, different sets of soil properties came out as indicators of soil quality related to management practices than those related to soil textural classes.

Compared to other studies (Wander and Bollero, 1999; Bredja et al., 2000a,b; Shukla et al., 2006), we did not detect just one soil property with the greatest potential for monitoring regional soil quality. Instead, our minimum data set includes 8 soil properties: three physical (AW, BD and MWD), four chemical (OM, Zn, Cu and Mn) and one biological (EN). However, if fewer soil properties were to be used to monitor soil quality in rice fields, as related to management systems and textural classes, micronutrients, specifically Cu and Mn, appear to offer the greatest potential, also for improving management systems.

Our approach selected OM, Cu, EN, Mn and MWD as the soil quality indicators to distinguish the soil management systems. Available water, BD and micronutrients (Cu, Zn, Mn) were the soil quality indicators to distinguish the soil textural classes. Using principal component analysis, Chaudhury et al. (2005) also reported that MWD was an important physical property to be retained in their minimum data set, while Mn was not considered an effective indicator of soil quality for different rice growing practices in India.

Mn was the only soil property correlated with yield, which suggests that the Mn concentration of soils has a strong influence on rice production. This micronutrient also contributed significantly to differentiating the management systems and soil textural classes. The speciation of Mn in soil is extremely complex and involves both chemical and microbial interactions (Fageira, 2001) and studies about micronutrients in lowland soil under inundation are scarce and contradictory (Assis et al., 2000). No Mn fertilization recommendations are supplied to the local farmers as it is assumed that the majority of the regional soils contain an adequate supply of micronutrients, including Mn (Manual, 2004). Consequently, the soil laboratories do not perform with any micronutrient analysis on a routine base. The results of this study suggests that Mn may have to be considered as a factor determining the sustainability of rice production in the region.

Farmers in the study area evaluate the production potential of the soils based on texture. Bulk density, AW, Zn, Cu and Mn are the soil quality indicators which were identified based on the textural classes. As Mn is also correlated with yield, it is probably sound to base farming practices on textural classes. None of the 7 other soil indicators identified in the discriminant analysis for both soil textural classes and management systems, could significantly predict yield. These other 7 indicators provide information on the most basic soil functions: water infiltration, storage and supply (AW, BD, MWD, OM, EN), nutrient storage, supply and cycling (OM, micronutrients, EN, AW) and sustaining biological activity (OM, EN). As a corroboration, OM and EN are widely recognized as useful indicators of all these soil functions together. Beyond that, OM is the simplest, least expensive to measure and EN is an indicator that farmers can observe themselves.

The statistical approach used here avoided arbitrary choices in selecting indicators within the significant principal components and discriminant analysis. Besides without performing separated analysis based on textural class and management system we would not have been able to decide whether the soil indicators would have been the consequence of inherent soil properties (i.c. texture) or management. The minimum data set, therefore, may provide an early warning tool to evaluate land management options, such as growing alternative crops and where to farm and buy land, or, in other words, to evaluate the sustainability of land use.

Further research is needed to validate our approach to arrive at the minimum data set in different regions, under different management and land use.

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Chapter 4

Functional evaluation of three soil quality indicator sets of three rice management systems

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Abstract

Efforts to define and quantify soil quality are not new, but establishing consensus about a set of standardized indicators remains difficult. Also, the view of land managers is usually not taken into account. The objective of this study was to compare, in functional terms, soil quality indices based on 29 soil quality indicators, 8 indicators selected from the 29 indicators that comprise a minimum data set and 4 indicators selected independently by farmers based on their own perception. Three different rice management systems were studied in Camaquã, Rio Grande do Sul state of Brazil. Considering 4 soil textural classes according to clay content (<20%, 20 - 40%, 40 - 60%, >60%) and 3 soil functions (water infiltration, storage and supply; nutrient storage, supply and cycling; and sustain biological activity), our study demonstrates that soil quality as a result of the management systems was best assessed when using the entire 29 indicators set. However, the fewer-indicators sets showed the same trends in differences between management systems, soil textural classes and soil functions and, hence, also provide meaningful information on soil quality for land management decisions.

Keywords: Soil quality index, soil quality indicators, farmers' knowledge, minimum data set, rice, Brazil

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4.1. Introduction

The need for understanding and assessing soil quality indicators has expanded because of growing public interest in determining the effects of land use and management practices on the quality of soil relative to sustainability (Schoenholtz et al., 2000). It has been identified as one of the most important goals for modern soil science (Wang and Gong, 1998).

Soil quality definitions have been proposed, emerging from different viewpoints in recent years (Doran and Parkin, 1994; Karlen et al., 1997, Doran, 2002), but there is no well-defined universal methodology to characterise soil quality and to define a set of clear indicators useful for soil quality assessment (Bouma, 2002).

One way to integrate information from soil indicators into the management decision process is to develop a soil quality index (Mohanty et al., 2006). When soil management focuses on sustainability rather than simply on crop yield, a soil quality index can be viewed as a primary indicator of the sustainability of land management (Andrews et al., 2002). The one most commonly used approach to develop an integrated soil quality index was suggested by Karlen and Stott (1994). They selected important soil functions associated with soil quality, such as accommodating water entry, accommodating water transfer and absorption, resisting surface degradation, and supporting plant growth to evaluate the effects of different types of soil management on soil quality. These functions were weighted and integrated according to the following expression:

$$\textit{Soil Quality Index} = q_{we}\,(wt) + q_{wt}\,(wt) + q_{rd}\,(wt) + q_{spg}\,(wt)$$

Where q_{we} is the rating for the soil's ability to accommodate water entry, q_{wt} is the rating for the soil's ability to facilitate water transfer, q_{rd} is the rating for the soil's ability to resist degradation, q_{spg} is the rating for the soil's ability to sustain plant growth, wt is the numerical weight for each soil function.

Soil quality indicators should be selected according to the soil functions of interest and threshold values have to be identified based on local conditions to generate the soil quality index. Which indicators to include in an index of soil quality is however a matter of debate. Given the complex nature of the soil and the very large number of soil indicators that may be determined, it is important to be able to select indicators that are appropriate for specific functions. Depending on the nature of the function under consideration the indicators actually selected will vary (Nortcliff, 2002). Indicator selection can be done using expert opinion or based purely on a statistical procedure to obtain a minimum data set (MDS).

According to Roming et al. (1995), using indicators of soil quality that have meaning to farmers and to other land managers is likely the most fruitful means of linking science with practice in assessing the sustainability of land management practices. A significant contribution to sustainable land management can be made by translating scientific knowledge and information on soil function into practical tools and approaches by which land managers can assess the sustainability of their management practices (Bouma, 1997, Doran, 2002).

In previous articles we presented a farmers' assessment of soil quality in rice production systems, resulting in 4 soil indicators (Lima et al., Chapter 2) and a formal scientific assessment of soil quality based on 29 soil indicators resulting in a MDS of 8 out of the 29 indicators (Lima et al., Chapter 3). The objective of the present paper is to evaluate these indicator sets in terms of discriminating power between three rice management systems in Camaquã, Rio Grande do Sul state of Brazil, using a novel tool of weighting the importance of soil quality indicators in terms of the soil functions suggested by Karlen and Stott (1994): water infiltration, storage and supply; nutrient storage, supply and cycling; and sustain biological activity.

In Camaquã, rice farmers are concerned about the deterioration of soil quality as a result of economy-driven changing in land management. We hypothesized that the 4 and 8 indicators sets would perform equally well as the 29 indicators set.

4.2. Material and Methods

4.2.1. Area description and soil sampling

Camaquã is located in the south of Brazil, in the Rio Grande do Sul state, latitude between 30º48'and 31º32' S, longitude between 51º47' and 52º19'W. Mean annual rainfall is 1213 mm and average temperature is 18.8ºC (Cunha et al., 2001).

Albaqualf and Humaquepts (Soil Survey Staff, 2006) are the two soil great groups found in this region. One of the main differences between and within these soils is the clay content in the topsoil (Cunha et al., 2001).

The growing period of rice in this region is from sowing between late September and early December till harvest in March-April. In the fallow period (between the harvest and soil preparation) the majority of the farmers have cattle in their fields. The three management systems differ with respect to intensity and timing of soil tillage and water use, as described in detail in Lima et al., Chapter 2) and summarized in Table 1 (Chapter 2).

Twenty-one rice fields from the two soil great groups under different rice management systems were selected. In each field, five replicate plots, 2x2 m each, were randomly laid out within an area of 3 ha. In total 105 representative plots were sampled from March to June 2004 (immediately after harvest). In each plot, 20 samples were taken from 0-10 cm depth across the sampling plot area. These samples were bulked and mixed for chemical, microbiological, and physical soil analyses. For some physical analyses, also three undisturbed soil cores were obtained from each plot. Earthworms were hand-sorted from a 30x30x30 cm monolith located in the central area of each plot.

4.2.2. Soil analysis

The physical, chemical and biological properties analysed are listed in Table 2. Detailed methods of analysis are given in Lima et al. (Chapter 3).

Table 2. Numeric weight associated to the 29 indicators set and soil functions used for soil quality index assessment

Soil function	Weight	Indicator Level 1	Weight	Indicator Level 2	Weight	Indicator Level 3	Weight
Water infiltration, storage and supply	0.33	Available water	0.20				
		Macroporosity	0.20				
		Earthworms	0.20				
		Correlated Indicators 1	0.20	Soil organic matter	0.33		
				Bulk density	0.33		
				Microporosity	0.33		
		Correlated Indicators 2	0.20	Water stable aggregate	0.50		
				Mean weight diameter	0.50		
Nutrient storage, supply and cycling	0.33	Available water	0.143				
		Macroporosity	0.143				
		Earthworms	0.143				
		Acidity/Al toxicity	0.143	pH	0.25		
				Potential Acidity	0.25		
				Exchangeable Al	0.25		
				Aluminum Saturation	0.25		
		Correlated indicators	0.143	Soil organic matter	0.33		
				Cation exchange capacity	0.33		
				Microporosity	0.33		
		Enzyme activity	0.143	ß-Glucosidase	0.33		
				Acid Phosphatase	0.33		
				Alkaline phosphatase	0.33		
		Nutrients	0.143	Phosphorus	0.143		
				Potassium	0.143		
				Manganese	0.143		
				Mineralizable N	0.143		
				Copper			
				Zinc	0.143		
				Correlated indicators	0.143	Calcium	0.25
					0.143	Magnesium	0.25
						Iron	0.25
						Total Nitrogen	0.25
Sustain biological activity	0.33	Microbial biomass	0.20				
		Soil organic matter	0.20				
		Earthworms	0.20				
		Microbial quotient	0.20				
		Microbial activity	0.20	Soil respiration	1.00		

4.2.3. Soil Quality assessment

A soil quality index was calculated using the approach suggested by Karlen and Stott (1994), in view of three soil functions: (1) Water infiltration, storage and supply, (2) Nutrient storage, supply and cycling, (3) Sustain biological activity. All three soil functions were assumed to be equally important in this assessment and were assigned weights of 0.33. The total of 29 soil quality indicators (Table 2) and the 8 indicators in the MDS (Table 3) were included in the three soil functions. This was not possible for the 4 farmers' indicators (Table 4), because the farmers consider all four interrelated in performing the three soil functions. In Tables 2-4 indicators have been assigned to different levels. Within each level, numerical weights were assigned to soil quality indicators based on their assumed importance to the particular soil function under consideration. All weights within level 1 must add up to 1.0. To avoid assigning overweight to redundant indicators in the 29 indicators set, a correlation analysis of the indicators was performed (Lima et al., - Chapter 3), which allowed us to have the correlated indicators (r>0.80) separated in groups and their weights equally distributed, as indicated in the next level (Table 2). This procedure was similarly considered in the MDS (Table 3). The farmers' indicators set included soil colour and friability, which have not been measured. For the purpose of the present study clay content and organic matter were chosen as proxies for soil colour and MWD as a proxy for friability. In Table 4, level 2 represents these proxies in the farmers' indicators set.

Table 3. Numeric weight associated to the minimum data set and soil functions used for soil quality index assessment

Soil function	Weight	Indicator Level 1	Weight	Indicator Level 2	Weight
Water infiltration, storage and supply	0.33	Available Water	0.25		
		Mean weight diameter	0.25		
		Earthworms	0.25		
		Correlated Indicators	0.25	Soil Organic matter	0.50
				Bulk Density	0.50
Nutrient storage, supply and cycling	0.33	Available Water	0.25		
		Earthworms	0.25		
		Soil organic matter	0.25		
		Micronutrients	0.25	Manganese	0.33
				Copper	0.33
				Zn	0.33
Sustain biological activity	0.33	Soil organic matter	0.50		
		Earthworms	0.50		

Using a scoring curve equation, three types of standardized non-linear scoring functions typically used for soil quality assessment (Karlen et al., 1994, Hussain et al., 1999, Glover et al., 2000) can be generated: (1) “More is better”, (2) “Optimum” and (3) “Less is better”. The equation defines a “More is better” scoring curve for positive slopes (e.g., organic matter), a “Less is better” curve for negative slopes (e.g., bulk density) and an “Optimum” scoring curve when a positive curve turns into a negative curve at a threshold value (e.g., pH). The shape of the curves generated by the scoring curve equation is determined by critical values. Critical values include threshold and baseline values. Threshold values are values of soil properties where the scoring function equals 1 when the measured soil property is at an optimum level or equals 0 when the soil property is at an unacceptable level. Baseline values are soil property values where the scoring function equals 0.5 and equals the midpoints between threshold soil property values (Glover et al., 2000).

Table 4. Numeric weight associated to the farmers’ indicators set and soil functions used for soil quality index assessment

Indicator Level 1	Weight	Indicator Level 2	Weight
Soil organic matter	0.25		
Earthworms	0.25		
Friability	0.25	Mean weight diameter	1.00
Soil colour	0.25	Clay	0.50
		Organic matter	0.50

Thus, numerical weights for each soil quality indicator are multiplied by indicator scores calculated through the use of standardized scoring functions that normalize indicator measurements to a value between 0 and 1.0. Scoring curves are generated from the following equation (Wymore, 1993):

$$= \frac{1}{[1 + ((B - L)/(x - L))^{2S(B+x-2L)}]}$$

where B is the baseline value of the soil indicator where the score equals 0.5, L is the lower threshold, S is the slope of the tangent to the curve at the baseline, x is the soil indicator value.

Threshold and baseline values are based on literature, specific data reference, expert opinion or measured values observed under near-ideal soil conditions for the specific site and crop (Burger and Kelting, 1999, Kelting et al., 1999). In this study, in the case of biological and physical indicators, threshold and baseline values were chosen according to the values from the data analyzed, because it was not possible to find a site that could characterize the natural soil condition in the region. For chemical indicators the threshold and baseline values were based on the literature (see Manual, 2004). This procedure was carried out for each group of indicators in each soil class studied (Tables 5).

Table 5. Scoring function values for evaluating soil quality in soil textural classes (% clay content)

		Class 1 (< 20% clay)					Class 2 (20-40% clay)			Class 3 (40-60% clay)			Class 4 (> 60% clay)		
Scoring curve	Indicator	LT	UT	LB	UB	O	LT	UT	LB	LT	UT	LB	LT	UT	LB
Physical properties															
More is better	Water stable aggregates	0	88	44			0	95	47.5	0	98	49	0	99	49.50
	Mean weight diameter	0	3	1.5			0	5	2.5	0	5.60	2.80	0	5	2.50
	Available water	0	0.14	0.07			0	0.09	0.05	0	0.08	0.04	0	0.10	0.05
	Microporosity	0	0.36	0.18			0	0.48	0.24	0	0.61	0.30	0	0.64	0.32
	Macroporosity	0	0.12	0.06			0	0.10	0.05	0	0.13	0.06	0	0.18	0.09
Less is better	Bulk density	1.50	2	1.75			1.30	2	1.65	0.75	1.75	1.25	0.75	1.75	1.25
Biological Properties															
More is better	Alkaline Phosphatase	0	17	8.5			0	42	21	0	144	72	0	116	58
	ß-Glucosidase	0	57	28.50			0	122	61	0	161	80	0	183	91.50
	Acid Phosphatase	0	206	103			0	350	175	0	506	253	0	525	262.50
	Soil Respiration	0	0.15	0.08			0	0.20	0.10	0	0.23	0.12	0	0.27	0.14
	Microbial Biomass	0	292	146			0	654	325	0	853	425	0	685	342
	Earthworms	0	360	180			0	660	330	0	303	151	0	482	241
	Microbial quotient	0	3.60	1.80			0	3.14	1.57	0	2.91	1.45	0	1.70	0.85
	Potentially-mineralizable N	0	47	23.50			0	64	32	0	72	36	0	74	37
Chemical properties (function values similar for all textural classes)															
More is better	Organic matter	0	5	2.5											
	Total N	0	0.40	0.20											
	Cation exchange capacity	0	15	7.5											
	Ca	0	4	2											
	Mg	0	1	0.5											
	K	0	180	90											
	P	0	12	6											
Optimum	Fe	0	63	17.50	49	35									
	Mn	0	18	5	14	10									
	Cu	0	2.70	0.75	2.10	1.50									
	Zn	0	3.60	1	2.80	2									
	pH	3	8	4.20	7	5.50									
Less is better	Al	0	2	1											
	Al sat	8	40	16											
	H+Al	0	9	4.5											

LT = Lower threshold; UT = Upper Threshold; LB = Lower Baseline; UB = Upper Baseline; O = Optimum

In short, the soil quality index is rated (between 0 and 1.0) when all indicators for a particular function have been scored by summing the products of the numerical weights and the normalized soil properties scores.

To calculate the soil quality index we used the SIMOQS (Sistema de Monitoramento da Qualidade do Solo) software developed in Viçosa Federal Univeristy, Brazil (see Chaer, 2001), using the model proposed by Karlen and Stott (1994).

Index outcomes were compared by using One-Way Anova with *post hoc* Bonferroni tests.

4.3. Results

The ability of the three sets of indicators to discriminate among management systems was examined. For the overall indexing results (Table 6) the semi-direct management system showed the highest quality index compared with the other management systems studied. No statistical differences among management systems were observed when the farmers' indicators set were used to calculate the overall soil quality index, but the same trend was observed as in the case of the 29 indicators set.

Table 6. Overall soil quality index values using three sets of indicators in the three management systems

Management Systems	29 Indicators set	Minimum data set	Farmers' indicators set
Semi-Direct	0.64a	0.56a	0.59a
Pre-germinated	0.53b	0.45b	0.57a
Conventional	0.50b	0.51ab	0.51a

Same letters in columns indicate that the SQI does not differ between management systems, using One-Way Anova with *post hoc* Bonferroni tests.

We also compared the soil quality indices per soil textural class (Table 7). The 29 indicators set discriminated best among the management systems, followed by the MDS and the farmers' indicators set. In general, the semi-direct management system again showed higher soil quality index values than the other management systems. Significant differences among the management systems were observed especially in class 3 for the three sets of indicators. In texture class 1, only the MDS showed significant differences among the systems while in texture classes 2 and 4 significant differences were only observed using the 29 indicators set.

Table 7. Soil quality index values using the three sets of indicators in each management system per soil textural class (% clay)

Management System	CLASS 1 (<20%)			CLASS 2 (20 - 40%)			CLASS 3 (40 - 60%)			CLASS 4 (>60%)		
	29 Indicators set	MDS	Farmers' indicators set	29 Indicators set	MDS	Farmers' indicators set	29 Indicators set	MDS	Farmers' indicators set	29 Indicators set	MDS	Farmers' indicators set
Semi-Direct	0.55a	0.44a	0.38a	0.65a	0.52a	0.53a	0.72a	0.68a	0.81a	0.63a	0.59a	0.64a
Pre-germinated	0.49a	0.26b	0.38a	0.52b	0.41a	0.49a	0.55b	0.52b	0.69b	0.54b	0.54a	0.64a
Conventional	-	-	-	0.52ab	0.51a	0.55a	0.47b	0.50b	0.45c	-	-	-

Same letters in columns indicate that the SQI does not differ between management systems, using One-Way Anova with *post hoc* Bonferroni tests.

When comparing the overall results per soil function (Table 8), the 29 indicators set and MDS had similar results in discriminating among the management systems. The highest soil quality values were found in function 1 ("water infiltration, storage and supply"). The semi-direct management system consistently showed a higher soil quality index than the other management systems in each soil function using these two indicator sets.

Table 8. Overall soil quality index values the 29 indicators set and the minimum data set (MDS) in each management system and for each of the three soil functions

Soil function	Management Systems	29 Indicators set	MDS
Water infiltration, storage and supply	Semi-direct	0.70a	0.67a
	Pre-germinated	0.62b	0.55b
	Conventional	0.67ab	0.54b
Nutrient storage, supply and cycling	Semi-direct	0.63a	0.50a
	Pre-germinated	0.55b	0.41b
	Conventional	0.58ab	0.51a
Sustain biological activity	Semi-direct	0.59a	0.51a
	Pre-germinated	0.42b	0.38b
	Conventional	0.25c	0.48ab

Same letters in columns indicate that the SQI does not differ between management systems, using One-Way Anova with *post hoc* Bonferroni tests.

Considering soil functions and management systems per soil textural class, the most evident differences occurred in class 3 and the highest values were found in function 1 (Table 9). Both the 29 indicators set and the MDS were consistent in showing the differences among management systems and functions in this class. In the texture class 1 only the MDS showed significant differences among management systems and functions. In general, the soil quality index calculated from the two sets of indicators showed that semi-direct was the management system that presented the highest values for all classes and functions studied.

Table 9. Soil quality index values using the 29 indicators set and the minimum data set (MDS) in each management systems, soil function and soil textural class (% clay)

Soil function	Management Systems	29 Indicators set	MDS
CLASS 1 (<20%)			
Water infiltration, storage and supply	Semi-direct	0.65a	0.56a
	Pre-germinated	0.63a	0.36b
Nutrient storage, supply and cycling	Semi-direct	0.62a	0.46a
	Pre-germinated	0.58a	0.31b
Sustain biological activity	Semi-direct	0.38a	0.29a
	Pre-germinated	0.28a	0.10b
CLASS 2 (20-40%)			
Water infiltration, storage and supply	Semi-direct	0.70a	0.60a
	Pre-germinated	0.60a	0.51a
	Conventional	0.70a	0.57a
Nutrient storage, supply and cycling	Semi-direct	0.64a	0.48a
	Pre-germinated	0.54a	0.39a
	Conventional	0.60a	0.48a
Sustain biological activity	Semi-direct	0.62a	0.47a
	Pre-germinated	0.41ab	0.33a
	Conventional	0.27b	0.50a
CLASS 3 (40-60%)			
Water infiltration, storage and supply	Semi-direct	0.78a	0.78a
	Pre-germinated	0.62b	0.60b
	Conventional	0.63b	0.49b
Nutrient storage, supply and cycling	Semi-direct	0.67a	0.58a
	Pre-germinated	0.55b	0.45b
	Conventional	0.55b	0.56ab
Sustain biological activity	Semi-direct	0.71a	0.68a
	Pre-germinated	0.49b	0.50b
	Conventional	0.23c	0.46b
CLASS 4 (>60%)			
Water infiltration, storage and supply	Semi-direct	0.65a	0.70a
	Pre-germinated	0.62a	0.64a
Nutrient storage, supply and cycling	Semi-direct	0.58a	0.49a
	Pre-germinated	0.53a	0.47a
Sustain biological activity	Semi-direct	0.65a	0.59a
	Pre-germinated	0.47b	0.51a

Same letters in columns indicate that the SQI does not differ between management systems, using One-Way Anova with *post hoc* Bonferroni tests.

4.4. Discussion and Conclusion

The index values indicated that the semi-direct management system resulted in the highest overall soil quality, followed by the pre-germinated and conventional systems. This implies that the soil functions considered are performed better in the semi-direct management system than in the pre-germinated and conventional systems. The soils under the semi-direct system are less mechanically affected by soil management practices than in the other systems.

Our results support the outcome of a study on soil quality indices of Glover (2000), who found that with less intensive tillage higher soil quality values were obtained than with conventional treatments. The lower soil quality indices under pre-germinated and conventional systems may be associated to the lower performance of function 3 ("sustain biological activity") found in this system. The significant differences among the management systems were the most pronounced for this function. This result, therefore, suggests that biological indicators are the most sensitive in indicating differences in soil quality under rice production systems.

Although, in some cases, the differences among management systems were not significant when we calculated the soil quality index from the MDS and farmers' indicators set, the most of the results presented the same trend as observed in the 29 indicators set. We infer, therefore, that fewer indicators can also discriminate soil quality among the management systems. This is consistent with findings of Andrews et al. (2002), who concluded that a reduced number of carefully chosen indicators could adequately provide the information needed for decision-making. Therefore, managers in our study area should pay special attention to the conventional and pre-germinated systems and particularly to their capability to sustain biological activity. In this sense, we agree with Kelting et al. (1999), who stated that soil quality index models are meant to provide an early warning tool that helps managers judge the positive and negative effects of their practices on sustainability.

The most pronounced differences among the management systems and functions were visible in soil textural class 3 for the three sets of indicators used. This result suggests that soil clay content between 40 and 60% considerably influences the performance of the soil quality functions.

Considering the absolute values, a score of 1.0 (or very close to 1.0) indicates that soil conditions have been maintained for both optimum rice production and optimum soil quality. In general, the highest scores were obtained for the semi-direct system for all soil functions. However, on average, the semi-direct system presented the lowest annual rice production (see table 1, chapter 2). This may be related to some specific soil properties/functions that are crucial for plant growth, which is also shown by the lowest scores in soil function 3. It suggests that the biological activity in this system has a stronger influence on the rice production than in other management systems.

Comparing the three sets of indicators, in general the highest absolute values of the indicators were observed in the 29 indicators set followed by the farmers' indicator set and the MDS. However, in the comparisons of the management systems, soil textural classes and soil functions, the indices in the 29 indicators set and MDS showed the same trend. This implies that the 8 indicators included in the MDS also represented the most relevant soil characteristics. This result, therefore, validates the statistical procedure we used to arrive at those indicators. Likewise, the results show that the rice farmers in the region appropriately chose the four indicators to characterize the quality of their soils for daily rice management decision-making.

It is known that the precision of soil quality assessment is increased by using as many indicators as possible, due to the very complex nature involving the physical, chemical and biological soil properties and their interactions. However, this study demonstrated that a few indicators, i.e. a MDS of 8 out of the 29 indicators or just 4 indicators as chosen by farmers, provided adequate information on soil quality differences among the management systems.

We conclude, therefore, that the soil quality index approach is an appropriate way for developing a quantitative procedure to evaluate the effects of land management practices on soil functions.

Further research is still needed to assess whether using those few indicators would be equally useful over time and in different management systems and land use. We suggest that a Decision Support tool be developed in co-operation with the farmers to arrive at better-informed land management decisions.

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Chapter 5

Management systems in irrigated rice affect physical and chemical soil properties

Abstract

Lowland soils are commonly found in the state of Rio Grande do Sul, Southern of Brazil, where they represent around 20% of the total area. Deficient drainage is the most important natural characteristic of these soils which therefore are mainly in use for irrigated rice. Degradation in these soils is progressively getting stronger since the intensity of agricultural activities leads to a higher soil density, and a lower water infiltration rate. This degradation has become an obstacle to establish other crops in rotation with (flood) irrigated rice. This study was done with the objective to assess the soil physical and chemical quality of the three rice management systems (Conventional, Semi-direct and Pre-germinated), most used in the region of Camaquã municipality (latitude between 30º48'and 31º32' S, longitude between 51º47' and 52º19'W), Rio Grande do Sul state, Brazil. Samples were collected from 21 rice farms with two different types of lowland soil (Albaqualf and Humaquepts). The soil samples were analyzed for physical and chemical properties. Using multivariate analysis of covariance (Mancova), the effects of the natural variability in terms of soil clay content were separated from the management effects. The analysis revealed that soil physical and chemical properties were also affected by the management practices adopted by farmers. The results showed that the major effect of the management systems was on a physical property: bulk density. An increase in soil density in the pre-germinated and conventional systems was found to be caused by a significant reduction in the microporosity, an indication of structural degradation. The semi-direct management system retained better soil conditions, associated with less intensive tillage operations and a better organic matter status. The chemical properties significantly affected by management (total N, Ca, Mg, Fe, Cation exchange capacity, and Potential acidity) all had their highest values in the semi-direct management system. This study confirmed that the physical soil degradation forms the main obstacle for growing other crops in a rotation with rice.

Keywords: Lowland, rice management systems, Brazil, physical and chemical soil properties.

A.C.R. Lima, W.B. Hoogmoed and E.A. Pauletto. Management systems in irrigated rice affect physical and chemical soil properties. (to be submitted)

5.1. Introduction

In many regions in Brazil human activity has caused environmental problems and unsustainable conditions in agricultural production areas. The lowland soils in the state of Rio Grande do Sul are one example of such a situation where the problems linked to the nature of the soils are intensified by agricultural activity. The impact of management systems used in these lowland soils is high and deserves special attention.

Twenty percent of the total area of Rio Grande do Sul state (approx. 5.4 million ha) is under lowland soil. Albaqualfs and Humaquepts are the two most important soil types found, covering 63% of the total lowland area of the state (Pinto et al., 2004). Deficient drainage caused by a dense and impervious B horizon is the most important characteristics of these soils. Due to this specific soil characteristic irrigated rice production is the most used crop adopted by regional farmers. With an annual production of approximately 5,5 million tons, equivalent to 52% of total Brazilian rice production, it has been the most important regional agricultural activity (Azambuja et al., 2004). This production involves puddling and keeping the area flooded for the duration of the rice crop. The importance of these soils, in terms of increasing agricultural production, resides in the possibility of their utilization with other crop production (Lima et al., 2002). However, studies have shown that wet tillage in rice can destroy soil structure (Tripathi et al., 2005) and creates a poor physical condition for the following crop because of its depressing effect on emergence, shoot and root growth (Mohanty et al., 2006).

Degradation of the regional soils, is mainly related to high soil density, low porosity, high micro/macro pores ratio, reduced hydraulic conductivity, and low water infiltration rate and it is progressively worsening because of the intensity of tillage applied in rice production (Pauletto et al., 2004). Accordingly, the level of degradation has become an obstacle for growing deeper rooting crops such as maize, soybeans or sorghum in rotation with flood irrigated rice (Lima et al., 2002).

Many soil properties have been proposed (Doran and Parkin, 1994; Schipper and Sparling, 2000, Mohanty 2007) as useful for soil quality monitoring. As the lowland soils assessed here are distinguished basically by texture (different surface clay content), in this study we are measuring some physical and chemical soil properties that may vary among different soil textures such as porosity, organic matter content, available nutrients etc.

Different management systems on lowland soils can affect differently the soil properties. Changes in soil properties can indicate the ability of soil to function effectively in order to supply water and may reflect limitations to root growth. A number of studies have assessed physical and chemical soil properties in lowland soils, in Brazil (Lima et al., 2002, Pedrotti et al., 2005, Lima et al., 2006, Reichert, 2006) and in other countries (Bhagat, 2003, Anders et al., 2005, Mohanty, 2007).

The majority of these studies were carried out in typical experimental sites with controlled treatments. In contrast, the study presented here is an analysis of soil properties collected from farmers' fields. An additional aspect is that we measured the net effect of the management systems on soil properties, i.e., after removing the effects of the intrinsic soil characteristic represented by the surface clay content.

In this context, it was hypothesized that rice management systems with less intensive tillage practices may lead to better (sustainable) physical and chemical soil conditions. For this, we investigated the soil quality of the three rice management systems, with varying degree of intensity and water use, from farmers' fields in the Camaquã municipality, Rio Grande do Sul state, Brazil.

5.2. Materials and Methods

5.2.1. Location and soils

Camaquã is located in the Coastal Province of the in the Rio Grande do Sul state, south of Brazil, latitude between 30º48'and 31º32' S, longitude between 51º47' and 52º19'W. Mean annual rainfall is 1213 mm and average temperature is 18.8ºC (Cunha et al., 2001).

Albaqualfs and Humaquepts (Soil Survey Staff, 2006) are the two soil great groups found in this region. The main differences between and within these soils is the inherent clay content found in the topsoil (Cunha et al., 2001).

5.2.2. Rice production management systems

The growing period of rice in this region is from sowing between late September and early December till harvest in March-April. In the fallow period (between the harvest and soil preparation) the majority of the farmers have cattle in their fields. The three management systems differ with respect to intensity and timing of soil tillage and water use.

5.2.2.1. Conventional

Just before the sowing period, the fields for rice are prepared when the soil is not inundated. This is done by deep (15-20 cm) tillage with a disc plough followed by superficial (10-15 cm) operations with a disc harrow with the aim to level the soil and prepare a seedbed of fine aggregates. Sowing is done with a conventional sowing machine. The fields are inundated after the seedlings have reached a height of approx. 10 cm.

5.2.2.2. Pre-germinated

The leveled fields areas are inundated in early August before the tillage operations start. In this condition, tillage is done in September and October. Usually, the same disced implements are used as in the conventional system, often complemented with a pass of a special leveller, made by heavy wood, to smoothen and level the puddled surface layer. Seeds are pre-germinated by soaking until the coleoptile is 2-3 mm long. Seeds are broadcast in the shallow (5-10 cm) water layer either by hand or sowing machine, depending on the size of the farm. The water layer allows a more precise levelling of the field and controls weeds.

5.2.2.3. Semi-Direct

The soil preparation is done in September or October (around 45-60 days before sowing) when the soil is not inundated. This early soil preparation with a disc plough and disc harrow permits the incorporation of the straw from the previous season and the germination of weeds. In November or December, a herbicide with total action is used to kill these weeds, and rice is sown without seedbed preparation, to avoid regrowth of weeds. Fields are inundated after emergence of the seedlings, as in the case of the conventional system.

A calendar of the three systems and the average monthly rainfall is shown in Table 1 (see Chapter 2).

5.2.3. Soil analysis

Twenty-one rice fields from the two soil great groups and under different rice management systems were selected (9 pre-germinated, 9 semi-direct and 3 conventional). In each field, five replicate plots, 2x2 m each, were randomly laid out within an area of 3 ha. In total 105 representative plots were sampled. From within each sampling area, 20 samples were taken from 0-10 cm depth using a hand auger and shovel. These samples were bulked and mixed for the analysis of chemical and physical soil characteristics. For those analyses requiring intact core samples (5cm diameter x 3cm), we obtained an additional three undisturbed soil cores from each plot.

All soil samples were collected immediately after the harvest of the 2004 season.

5.2.3.1. Physical

Bulk density (BD), soil particle size distribution, water stable aggregates (WSA), microporosity (MiP ≤ 0.05 mm), and soil water retention on pressure plates at field capacity and permanent wilting point (-340 and -1500 kPa) were analysed according to methods described by Klute (1986). Water stable aggregate was determined by wet sieving (through sieves of size 9.52, 4.76, 2.00, 1.00, 0.25 and 0.105 mm). The total aggregate weight was then the sum of each sieve. Available water (AW = difference between water content at field capacity and permanent wilting point), macroporosity (MaP = difference between total porosity and MiP) and mean weight diameter (MWD = Σ (mean diameter x aggregates weight) / sample dry weight) were calculated from the measured data set.

5.2.3.2. Chemical

Thirteen chemical properties including micronutrients were chosen to be analysed, based on common practice in the region. All properties were assessed but for this study we have taken the only ones most correlated (r>0.70) with organic matter (OM): Total N (TN), Ca, Mg, Fe, Potential Acidity (PA) and Cation Exchange Capacity (CEC) (Table 4). Reasons were: a) OM plays a role in almost every soil function, and b) OM varies among different soil textures (surface clay content).

Samples were analysed for OM using the Walkley-Black method, Total N (TN) using the Kjeldahl method. Exchangeable Ca and Mg were extracted by 1M KCl and determined by atomic absorption spectrometry. PA was estimated by SMP buffer solution and CEC as sum of bases + (PA). Fe was determined by atomic absorption spectrometry and extracted by 0.2M ammonium oxalate at pH 3,0.

5.2.4. Statistical analysis

To eliminate the effects of the intrinsic soil characteristic, i.e., clay content (covariate) on the physical and chemical proprieties (dependent variable) we used Multivariate Analysis of Covariance (Mancova) for checking whether the management systems (fixed factor) effects were still significant after removing the effects of clay content. Mancova helps to exert a stricter control by taking account of the confounding variable textural properties on the soils properties analysed. In so doing, a purer measure of effect of the interested variable can be obtained. The data were analysed using SPSS software (SPSS, 1998) and the main effect comparisons were estimated with Bonferroni post hoc tests. Correlation between physical and chemical properties was also performed for supporting the analyses.

5.3. Results and discussion

Tables 2 and 3 show that most of the soil physical and chemical properties studied differed significantly among the three management systems. For the analyses of both physical and chemical properties the values of F-rations (Wilks's Lambda) reached the criterion for significance, indicating that between-group differences exist after removing the covariate effect.

Table 2. Estimated soil physical properties marginal means and Standard deviations (Sd).

Management Systems	BD		MiP		MaP		AW		WSA		MWD	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Semi direct	1.15a	0.42	0.49a	0.14	0.08a	0.02	0.08a	0.03	87.40a	10.19	2.99a	1.36
Pre-germinated	1.30b	0.24	0.44b	0.09	0.09a	0.04	0.06b	0.02	88.85a	9.12	3.84a	1.29
Conventional	1.34b	0.14	0.42b	0.06	0.09a	0.02	0.06b	0.02	84.70a	6.07	2.74a	0.71

Wilks's Lambda = .40, F (2, 101) = 9.24, p<0.001.
Same letters in columns indicate that the soil physical property does not differ between management systems, using Mancova with *post hoc* Bonferroni tests. Evaluated at covariates appeared in the model: % Clay = 44,41.
BD: Bulk Density, MiP: Microporosity, MaP: Macroporosity, AW: Available Water, WSA: Water Stable Aggregate, MWD: Mean Weight Diameter.

Table 3. Estimated soil chemical properties marginal means and Standard deviations (Sd).

Management Systems	OM		TN		Ca		Mg		Fe		PA		CEC	
	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd	Mean	Sd
Semi direct	6.77a	4.03	0.44a	0.31	6.93a	3.52	1.84a	0.94	33.09a	15.62	12.25a	7.35	21.25a	11.38
Pre-germinated	4.27b	2.05	0.22b	0.16	5.19b	2.69	1.59a	0.87	32.78a	14.65	8.38b	4.94	15.44b	7.85
Conventional	4.02b	0.97	0.19b	0.07	3.93c	1.34	1.85a	0.77	21.93b	4.25	11.80a	5.98	17.92b	7.76

Wilks's Lambda = .19, F (2, 101) = 17.41, p<0.001.
Same letters in columns indicate that the soil physical property does not differ between management systems, using Mancova with *post hoc* Bonferroni tests. Evaluated at covariates appeared in the model: % Clay = 44,41.
OM: Organic Matter, TN: Total N, PA: Potential Acidity, CEC: Cation Exchange Capacity.

The conventional management system presented the highest BD, and the lowest MiP. For both properties the conventional system showed a significant difference with the semi-direct systems. As only small and non-significant differences in macroporosity were found between systems, it is obvious that microporosity was responsible for the BD differences.

This is consistent with findings of Lima et al. (2006) who studied similar irrigated rice systems on lowland experimental sites in Pelotas, Rio Grande do Sul. Table 4 shows that there is indeed a significant correlation between these two properties.

Table 4. Correlations between physical and chemical soil properties (*n=105*)

Indicators	OM	TN	P	K	Ca	Mg	Al	Cu	Zn	Fe	Mn	PA	Al sat	BD	MiP	MaP	AW	WSA	MWD
OM																			
TN	**,950**																		
P	,101	,117																	
K	,150	,086	,293																
Ca	**,940**	**,869**	,140	,247															
Mg	**,749**	,623	,166	,430	**,856**														
Al	,563	,676	-,041	-,080	,385	,189													
Cu	-,191	-,303	-,206	,480	-,037	,137	-,193												
Zn	,345	,245	,238	,591	,535	,615	,015	,648											
Fe	**,742**	,652	,142	,412	**,813**	**,746**	,292	,177	,607										
Mn	,157	,053	-,135	,596	,164	,426	,148	,487	,404	,243									
PA	**,849**	**,828**	,010	,104	**,765**	,632	**,709**	-,205	,231	,585	,295								
Al sat	-,292	-,142	-,273	-,363	-,486	-,563	,506	-,180	-,488	-,383	-,106	-,063							
BD	**-,947**	**-,926**	-,134	-,276	**-,923**	**-,772**	-,584	,074	-,462	**-,753**	-,268	**-,817**	,267						
MiP	**,923**	**,880**	,220	,313	**,929**	**,813**	,499	-,052	,520	**,769**	,278	**,802**	-,373	**-,949**					
MaP	,023	,040	-,270	-,022	,003	-,055	,008	-,059	-,197	-,025	,012	,054	,068	-,069	-,150				
AW	-,251	-,235	,049	-,274	-,291	-,255	-,266	-,248	-,315	-,314	-,219	-,275	,020	,326	-,319	,101			
WSA	,660	,641	,096	,366	,695	,577	,431	,160	,474	,661	,216	,583	-,211	**-,722**	,697	,095	-,442		
MWD	,575	,538	,094	,389	,664	,585	,371	,313	,648	,648	,240	,482	-,252	-,667	,681	-,046	-,494	**,845**	
CEC	**,932**	**,883**	,070	,195	**,907**	**,788**	,607	-,130	,386	**,719**	,291	**,963**	-,253	**-,909**	**,905**	,031	-,301	,663	,589

Al sat: Al saturation, AW: Available Water, BD: Bulk Density, CEC: Cation Exchange Capacity, MaP: macroporosity, MiP: Microporosity, MWD: Mean Weight Diameter, OM: Organic Matter, PA: Potential Acidity, TN: Total N, WSA: Water Stable Aggregates
Significant correlations (r>0.7) are presented in bold type

The lowest soil BD value in the surface layer was observed in the soil under the semi-direct system. Our results confirm the results of research reported by Pedrotti et al. (2001) showing that rice production fields on Albaqualfs in the same region under less intensive tillage practices presented the lowest BD values. Table 3 also shows that OM contents in the soil under the semi-direct system were significantly higher than in soils under the other two systems (a mean value of 6.77% as compared to 4.02% in the conventional system). These values, were obtained after removing the natural effect, of clay content on OM, using an estimation by the Benferroni method. In these lowland soils, soil moisture and OM are the two factors which may explain why differences in bulk density were found and were associated to microporosity and not to macroporosity:

(a) the moisture conditions during the major field operations are adverse: natural deficient drainage caused by a dense and impervious B horizon leads to very wet soil conditions during periods of soil preparation, sowing and harvest, a problem which cannot be solved by draining irrigation water because usually rainfall is high during the non-irrigated periods (Table 1, Chapter 2),

(b) different rice varieties are used by farmers for each system, so the amounts of biomass produced and left in the field (including the roots) may differ. More biomass is left in the semi-direct system and less exposure to sun and rain leads to lower losses of OM.

Reduced microporosity indicates a deterioration of soil structural quality which is difficult to reverse due to the long wet periods. Puddling is a rather extreme form of tillage with a strong impact on soil structure because it results in aggregate breakdown and the destruction of macropores (Ringrose-Voase, 2000). Aditionally, an aggregate that is stable to wetting by water must be held together by relatively strong chemical bonds (Harris et al., 1966). Over time a decrease of bulk density, under these conditions, can only be expected as a result of an increase of organic matter content (Pedrotti et al., 2005).

No statistical differences among management systems were observed for WSA and MWD (Table 2). The highest mean values for WSA and MWD, though, were recorded in the pre-germinated system. Figure 1 shows that this effect cannot clearly be attributed to different levels of clay content in the soils that are under this system (see Figure 1). Although clay content will have an affect on soil structural properties in lowland rice soils as e.g. reported by Mambani et al., (1990) and Reichert et al., (2006), in this case there will be an effect of OM as well.

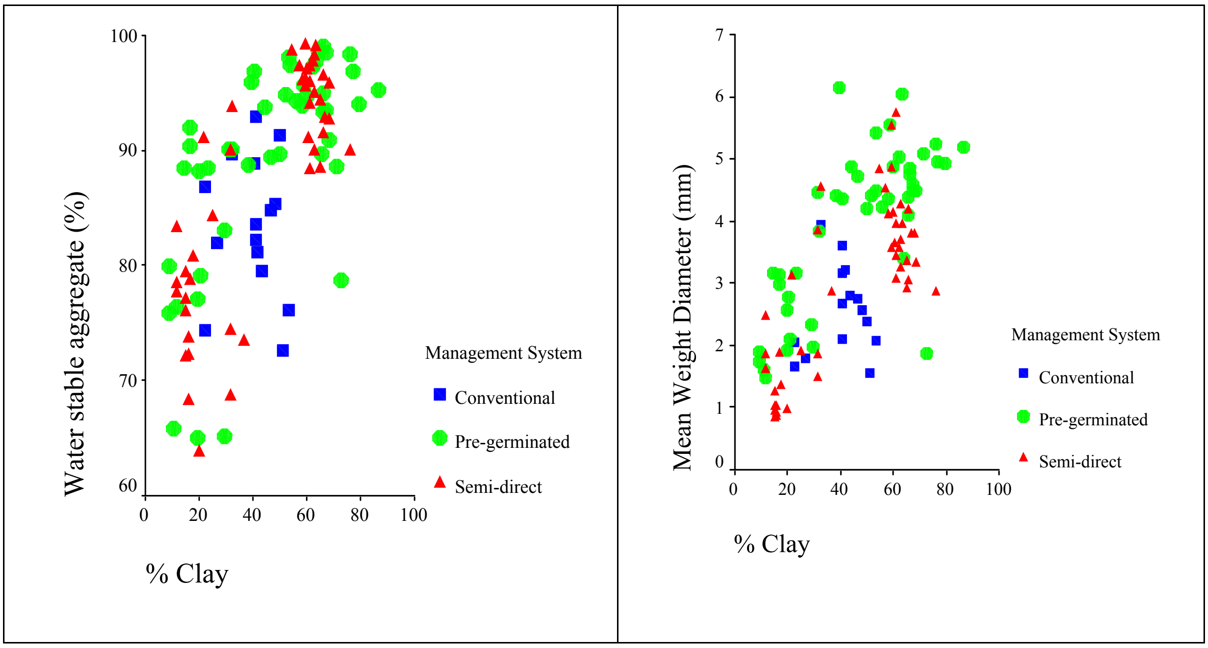

Figure 1. Relationship between soil physical properties and soil clay content in the three management systems

When considering the correlations between properties as shown in Table 4, changes in BD were mostly correlated with MiP and OM followed by 6 chemical properties (TN, Ca, CEC, PA, Mg, Fe) and 1 physical property (WSA). These relationships were to be expected because of all of these properties had high correlation with each other and also with OM.. With exception of Mg, all soil chemical properties differed among the three management systems (Table 4). All chemical properties had their highest value for the semi-direct system.

As our data came from farmer's fields, they reflect the reality of the region and the farmer's interference. The variability of the results on the pre-germinated and semi-direct systems was clearly illustrated by a farmer who stated that:

"...Pre-germinated and semi-direct management systems is like a dancing party: everybody dances but no one dances exactly in the same way" (quoted from Hélio Duarte).

5.4. Conclusions

The results showed that the major effect of the management systems was on a physical property: bulk density. An increase in soil density in the pre-germinated and conventional systems was found to be caused by a significant reduction in the microporosity, an indication of structural degradation. The semi-direct management system retained better soil conditions, associated with less intensive tillage operations and a better organic matter status. The chemical properties significantly affected by management (total N, Ca, Mg, Fe, Cation exchange capacity, and Potential acidity) all had their highest values in the semi-direct management system.

It is proved that it is possible to separate by statistical methods the effects of the natural variability in terms of soil clay content from the management effects on the physical and chemical properties. This allowed an analysis of the changes in soil quality due to management activities based on data collected from non-experimental (farmers') fields.

As sampling was done immediately after harvest, the analysis showed the long-term detrimental effect of tillage under adverse conditions, and not the short-term tillage effect which typically is an increase in macroporosity.

It can be affirmed that the soils studied are suitable for irrigated rice production, and soil chemical and physical degradation has not yet been an obstacle to obtain high rice yields.

However, as chemical deficiencies can be overcome rather easily, physical degradation is responsible for the problems which farmers experience in growing crops other than rice.

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Chapter 6

Earthworm diversity from Rio Grande do Sul, Brazil, with a new native Criodrilid genus and species (Oligochaeta: Criodrilidae).

Abstract

This paper presents the state of knowledge of the earthworm diversity in Rio Grande do SuI, Brazil, including the species recently found in rice fields and adjacent ecosystems in the Camaquã region. Current earthworm diversity in this state shows a total of 36 species and 20 genera, belonging to seven families. Glossoscolecidae is the most diverse (ten species) and represents 27.7% of the total fauna. Approximately 35% of the genera and 41.7% of the species are natives, while 65% of the genera and 58.3% of the species are exotics. Native species are dominated by Glossoscolecidae whereas exotic species are Lumbricidae and Megascolecidae. In this study, nine species are new records for the Camaquã region, two species are reported for the first time from the state of Rio Grande do Sul and a new native genus and species of Criodrilidae is described.

Keywords: Oligochaeta, Taxonomy, Earthworm diversity, Brazil, *Guarani camaqua* gen. et sp. nov.

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6.1 Introduction

It was calculated that the world's oligochaeta fauna comprised 9500-10300 species, 5900 of which were terrestrial earthworms (Blakemore, 2006). New species have been described at an estimated average annual rate of 68 (Reynolds, 1994).

Brazil is a megadiverse country with paleo-geographical, ecological and climatic conditions supporting one of the most diverse earthworm faunas in the world (James and Brown, 2006). The first earthworm list for the country was presented by Michaelsen (1927) with 51 species. Seventy-nine years later, James and Brown (2006) report that more than 290 species are known and they estimate that Brazil has as many as 2720 species. The knowledge of Brazilian earthworm taxonomy was mainly gathered by Dr. Gilberto Righi who described 139 megadrile species, 20 megadrile genera, and one megadrile family during his life (Mischis and Reynolds, 1999; Fragoso *et al.*, 2003).

Regarding to Rio Grande do Sul state in southern Brazil, the first report about earthworm diversity was published by Michaelsen (1892), who mentioned *Eisenia foetida* (Savigny 1826), *Aporrectodea rosea* (Savigny 1826), *Aporrectodea trapezoides* (Dugès 1828), *Amynthas gracilis* (Kinberg 1867), *Glossoscolex grandis* (Michaelsen 1892) and *Urobenus brasiliensis* Benham 1887. Other species were added by Üde (1893), Černosvitov (1942), Cordero (1943), Righi (1965; 1967a,b; 1971a,b), Knäpper (1972a,b; 1977) and Knäpper and Porto (1979). Taxonomic earthworm research in the region has dramatically decreased since the end of 1970s.

In late 2003 during the first Latin American meeting on earthworm ecology and taxonomy held in Londrina, Brazil, Dr. Christa Knäpper[2] reported that a total of 15 species are known from Rio Grande do Sul. These species belong to the families Lumbricidae (4 spp.), Criodrilidae (1 sp.), Glossoscolecidae (2 spp.), Ocnerodrilidae (1 sp.), Megascolecidae (6 spp.) and Octochaetidae (1 sp.). Knäpper also reported that only 33 out of 497 municipalities in the state have been sampled so far. The data were geographically dispersed point sources and a recent overview of the existing species in the region does not exist.

Due to the fact that recent earthworm taxonomy research has been practically absent, earthworm diversity literature for Rio Grande do Sul is incomplete, scattered and outdated. This paper has the objective to present the state of knowledge of the earthworm diversity in

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[2] Oral presentation

Rio Grande do Sul. It includes data of a recent survey from an unsampled regional rice fields and adjacent areas of Camaquã, and the description of a new native criodrilid genus and species.

6.2 Material and Methods

Earthworms were collected in 21 rice fields and 8 adjacent areas in Camaquã region. Camaquã is located in the south of Brazil, in the Rio Grande do Sul state, between latitude 30°48' and 31°32' S, and longitude 51°47' and 52°19'W. Samples from rice fields were taken from April to July 2004 after harvesting and samples from adjacent areas were taken in July 2004 and June 2005. Protocols of the Tropical Soil Biology and Fertility (TSBF) (Anderson and Ingram, 1993) were applied, involving hand-sorting of 30 x 30 x 30 cm square soil monoliths. In each field, five replicate monoliths were randomly laid out within an area of 3 ha. In total 145 representative monoliths were sampled. The sampled worms were fixed and killed directly in a formalin solution (5%). Specimens were deposited in the Ana Cláudia Rodrigues de Lima (ACRL) collection. In the future, some types will be deposited in the Museum of Zoology in São Paulo, Brazil.

Criteria were followed for earthworm identification and valid names updating as described by Sims and Easton (1972) and Blakemore (2002, 2005) for Megascolecidae, Brinkhurst and Jamieson (1971) for Glossoscolecidae, Blakemore (2005) for Lumbricidae and Criodrilidae, and Jamieson (1970) for *Eukerria*. Native fauna are considered those earthworms that originate somewhere in the Neotropical region. The exotics are ones (accidentally) introduced into these areas.

The list of earthworm diversity from Rio Grande do Sul was completed by reviewing all available literature referring to the state.

6.3 Results

New Taxa

FAMILY CRIODRILIDAE Vejdovský 1884

Genus *Guarani* Rodríguez et Lima gen. nov.

Type species:

Guarani camaqua Rodríguez et Lima sp. nov.

Etymology: The name refers to one of the first indigenous population of the region of Rio Grande do Sul. It is masculine in gender.

Diagnosis: Body quadrangular in cross section in and behind clitellar region. Dorsal groove and lateral lines absents. Anus dorsal, subterminal. Setae eight by segment, closely paired, *dd* < 0.3 u. Clitellum annular, indistinctly delimited anteriorly and posteriorly in 17, 18 - 34, 35, 36, 37. Male pores on porophores in 15 in front to clitellum. Female pores slightly median to *a* setae. Spermatic pouches usually present on the body wall in 14 segment, near 13/14. Paired septal pouches beginning from segment 13. Oesophageal musculature slightly thickened in the region of 5-7. Intestine beginning in 18. Dorsal typhlosole present. Hearts in 7-11. Supraesophageal vessel present. Subneural vessel adherent to the body wall. Nephridia beginning posterior to segment 13. Holandric. Testis sacs absent. Paired seminal vesicles in 11, 12. Vasa deferentia intraparietal. Bursae or prostates like glands present in segment 15. Metagynous. Big paddle-shaped ovaries present. Oocytes not forming egg-strings. Spermatecae absent.

Guarani camaqua Rodríguez et Lima sp. nov. (Figure 1)

Material Examined:

Holotype. (ACRL 001) BRAZIL, Rio Grande do Sul state, Camaquã, between latitude 30°48' and 31°32' S, and longitude 51°47' and 52°19'W, rice field, 3 May 2004, Lima (hand-sorting).

Paratypes. (ACRL 002-005) 4 (adults), same data as for holotype.

Other material: (ACRL 006-011) 3 (adults) 3 (subadults), 27 July 2004. Same data as for holotype.

Etymology: The specific name is a noun in opposition and refers to the place where the species was collected. The word Camaquã has an indigenous origin and comes from Tapes Indian language.

Diagnosis. As for the genus, the species can also be distinguished by the size, prostomium type, colouring, and papillae pattern.

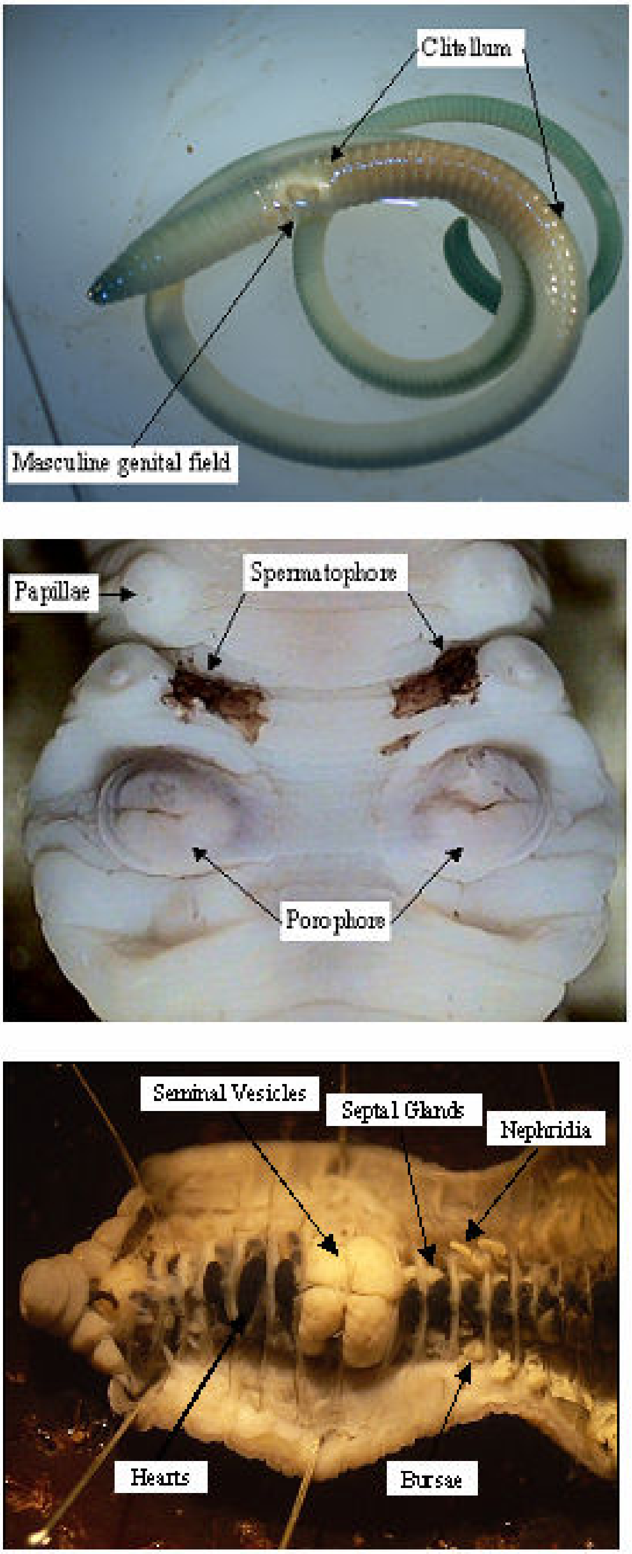

Fig. 1 *Guarani camaqua* gen. et sp. nov. (Paratype). Some of the anatomical characteristics.

Description

External Morphology

(Holotype). Total body length 180 mm, diameter: 4.0 mm postclitellar (at segment 40), 374 segments. Body cylindrical before clitellum and quadrangular in and behind clitellar region, hind body almost square in cross section. Dorsal surface slightly concave at the end of the body, ventral surface similar or flattened. Preclitellar segments with weakly secondary annulations. Dorsal groove and lateral lines absents. Green pigmentation present dorsally to lateral, mainly in the anterior and posterior ends, green-brownish at the mid-body and dark brown in clitellar region (green-grayish body and ochre clitellum in formalin preservation). Prostomium zygolobous. Anus dorsal, subterminal. Setae fairly closely paired throughout, located at the angles of the body in cross section, beginning at 2; setal formula *aa:ab:bc:cd:dd* = 7.1:1:8:1:10.6 at 10, 7.7:1:8:1:11.7 at 40, *dd* ≈ 1/4 circumference throughout; somatic setae 0.64 x 0.035 mm bearing weak subapical scarces; ventral setal couples of segments 13, 14 and 16 each on an ovoid prominence or crescentic papillae, whitish, 0.61-0.64 x 0.035 mm, unornamented (genital?). Nephropores inconspicuous at *AB* level (internal observation). Clitellum annular, indistinctly delimited posteriorly, embracing 17, 18 to 34, 35, 36, 37 (=18-21 segments), setae and intersegmental furrows evident, conspicuous. Genital male field involves an expanded ventro-lateral tegumentary area hardly thickened in segments 15 and 16, widest in 15, butterfly-shaped; male porophores strongly protuberant, transversally placed at *AB* level, bearing several concentric folders around the slit-shaped and transverse male pores in 15, mid-ventral area of this field not glandular, so intersegmental furrows are visible; genital male field pushs intersegments 14/15 and 16/17 apart. Paired whitish crescent papillae bearing setae ab in 13, 14 and 16. A pair of mass or membranous bags containing a white substance (sperm?) attached at 13/14 in setae *AB* line, partially extended to mid-ventral line. Female pores inconspicuous, slightly median to setae (internal observation). Dorsal and spermathecal pores absent.

Internal Morphology

Body wall musculature very thick. Septa muscular, 4/5 slightly so, greatest thickness at 9/10 and 10/11, then, musculature gradually begins to decrease. Paired septal glands or pouches attached at posterior face of each septa beginning in 13, the first ones acinous, decreasing in size and disappearing gradually in the vicinity of segment 40 or even before, ventra-lateral, the last ones at each side of mid-ventral line. Oesophageal musculature appreciably thickened in segments 5 and 6, where oesophagus appears widened, slightly in 7. Calciferous glands absents. Intestine commencing in 18, with distinctive oesophageal valve in 16-17. Typhlosole beginning indistinctly in the vicinity of segment 25 as a low thick ribbon, becoming a thick lamella after 30 to almost the last segments, maximal height of a half intestine diameter. Hearts in 7-11, at least 11 latero-oesophageal. Supra-oesophageal vessel from, at least segment 7, to 13; dorsal vessel continuous onto the pharynx; median subneural vessel present throughout adhering to body wall. Holonephric, nephridia commencing in segment 16, ducts avesiculate, entering the parietes in front of setae *ab*. Testes and funnels free in 10 and 11, abundant sperm masses in each segment. Paired seminal vesicles in 11 and 12, voluminous, with dense tissue, filling each segment to dorsal line, the pair in 12 largest. Vasa deferentia concealed deeply in the thick body wall musculature, emerging in the coelom of 15 where that of each side of the body joins a large hemispherical male bursae or pouche which are located in line with *AB* line, coinciding with the external opening of the porophores. Big paddle-shaped ovaries showing numerous oocytes, not forming egg-strings and silvered plicate funnels in anterior face of 13/14. Spermathecae absent.

Variability: Scarce variability was observed in relation to length, clitellum, and sex external characteristics (Table 1).

Table 1. Variability of some external anatomic characteristics in *Guarani camaqua* gen. Et sp. nov.

Earthworm specimen	Length (mm)	Diameter (mm)	Number of segments	Clitellar development	Genital markings
1.Holotype	180	4.0	374	1/n, 17(18-34)1/n 36	Papillae in13,14,16; Porophores in 15
2.Paratype 1	145	5.2	284	1/n, 17(18-34)1/n 36	Typical (like Holotype)
3.Paratype 2	146+	4.5	232+	1/n, 17(18-35)1/n 36	Typical
4.Paratype 3	145+	4.5	268+	1/n, 17(18-36)1/n 37	Typical
5.Paratype 4	117+	4.0	268+	1/n, 17(18-35)1/n 36	Typical
6	128	3.5	251	1/n, 17(17-34)1/n 35	Typical
7	126	3.0	279	subadult	1 pair marks in 15
8	138	4.0	322	subadult	Pairs in 13, 14, 15,16
9	140	3.5	320	subadult	Pairs in 13, 14, 15,16
10	167	3.1	261	(18-35)	Typical
11	204	3.1	321	(18-35)1/n 36	Typical

6.4 Discussion

South and Central American species included in *Criodrilus* Hoffmeister, 1845 (syn. *Hydrilus* Qiu and Bouché, 1998 according to Omodeo and Rota, 2004 and Blakemore, 2005) were transferred by Michaelsen (1918) to *Drilocrius* Michaelsen, 1917 (Family Almidae) as they possessed spermathecae rather than spermatophores. Also Brinkhurst and Jamieson (1971) excluded *Criodrilus bathybates* (Stephenson, 1917) from this genus to make it the type species of *Biwadrilus* Brinkhurst and Jamieson, 1971 and considered *Criodrilus ochridensis* Georgevitch, 1950 as a species *inquerendae.*

In an update checklist of valid names of superfamilies Criodriloidea and Lumbricoidea, Blakemore (2005) cited two species for the only single family and genus of Criodriloidea, *Criodrilus lacuum* Hoffmeister, 1845 and *C. ochridensis.*

We propose the genus *Guarani* to accommodate the new South American species. A hemispheroidal bursae externally opening in male pores on porophores in 15, spermathecae absent and paddle-shaped ovaries (although very big) not forming egg-strings are present in G. *camaqua,* which are consistent to Criodrilidae.

Anatomic characteristics of the new species, described here, also showed important taxonomic differences related to the definition of genus *Criodrilus,* so *Guarani* can be separated from *Criodrilus* mainly because of the presence of supraoesophageal vessels and septal pouches, seminal vesicles number reduced to two pairs located in segments 11 and 12, the posterior position of clitellum, intestine and nephridia commencing posterior to segment 15, masculine pores in front of clitellum, spermatophores not tubular or horn shaped, genital papillae pattern and its disjointed geographical distribution with relation to *Criodrilus* (mainly European). Some of these taxonomic differences are clearly presented in the Figure 1.

The appearance of a new criodrilid species, *Guarani camaqua*, in highly disturbed areas, such as rice fields, at a distance from native regional populations (of the exclusively holartic family Criodrilidae), while knowing that C. *lacuum* is a widely introduced and frequently a parthenogenetic species, it could be considered that we have of a simple morph of *C. lacuum.* Thus, causing it to fall into a long list of synonyms for *C. lacuum.* However, some anatomical differences between *G. camaqua* and *C. lacuum* are not only sexual characters (which are generally more susceptible to suffering missing structures, or reduction in the size, number and position in the parthenogenetic forms), but also, somatic characters involving the digestive, vascular and nephridial systems. The presence of a supraesophageal vessel is a uniquely important taxonomic character at the supraspecific level, which justifies the separation proposed in this study.

We also want point out that all reviewed clitellate specimens exhibited good development of the seminal vesicles, iridescence on male funnels and spermatophore masses indicating mature male reproductive organs. According to those specific characteristics there is limited probability they are parthenogenetic individuals. Any significant morphological and/or anatomical variation in C. *lacuum* through all its geographical distribution was discussed by Omodeo and Rota (2004). Thus, the discovery of a new criodrilid species in South America with these structural differences is inconsistent with some degenerative form of C. *lacuum*. Our species, therefore, should be considered, at least for the present moment, as a new genus and species.

In spite of the presence of a supraoesophageal vessel and a subneural vessel not adherent to the nerve cord in *G. camaqua* (characters included at super-familiar level) (see Sims 1980), we have preferred to include it for the moment, in the new genus within the family

Criodrilidae, mainly due to the presence of copulatory bursae or "prostatic like" bursae and the absence of spermathecae (Brinkhurst and Jamieson 1971; Sims 1980; Blakemore 2000).

The supraoesophageal and subneural vessel adherent to body wall are inherent characteristics of superfamily Glossoscolecoidea, family Almidae (Sims, 1980). Many other classifications have been produced (Bouché 1983; Omodeo 1998, 2000) which were not consistent to each other, due to a heterogeneous choice of taxonomic characters even at high taxonomic categories. Particularity, Omodeo (2000) proposed to regroup 11 aquatic genera of megadriles from Lumbricoidea in only three families: Criodrilidae (holartic; *Criodrilus, Sparganophilus, Komarekiona, Lutodrilus, Biwadrilus),* Glyphidrilidae (South America, central-eastern Africa, India, Indonesia; *Areco, Drilocrius, Glydrilocrius, Callidrilus, Glyphidrilus)* and Almidae (Africa, *Alma). G. camaqua* is not consistent with this divisions; because the ovaries-shape differs of Omodeo's Criodilidae. Besides that the position of oesophageal hearts and clitellum differs of Glyphidrilidae. Hence, the presence of this particular structure arrangement in G. *camaqua* also suggests that a deep taxonomic revision should be done. Discovery of more species in a region scarcely studied like Rio Grande do Sul, or even southern Brazil in general, would probably lead to a systematic rearrangement of the group.

6.5. Earthworm diversity of Rio Grande do Sul

This study shows that earthworm diversity of Rio Grande do Sul is expressed in 36 species and 20 genera, belonging to seven families. Glossoscolecidae are the most diverse (10 species) and represent 27.7% of the total fauna. Approximately 35% of the genera and 41.7% of the species are natives, while 65% of the genera and 58.3% of the species are exotics. Native species are dominated by Glossoscolecidae whereas exotic species are Lumbricidae and Megascolecidae (Table 2). The small number of sites sampled and the fact that the majority of these samples were taken from disturbed areas may explain the low number of natives found so far.

According to James and Brown (2006), only 14% of the total Brazilian species are exotics. They are widespread, mainly due to the human activities over centuries. Some Acanthodrilidae and Lumbricidae have a more restricted distribution in the south of Brazil, mainly in Rio Grande do Sul where the cool climate is more like their native homelands in the

Northern hemisphere. We are reporting an even larger rate of exotic species in Rio Grande do Sul which agrees with the above statement.

Table 2. Native and exotic earthworms from Rio Grande do Sul, Brazil

Earthwom families	Native		Exotic		Total	
	Genera	Species	Genera	Species	Genera	Species
Acanthodrilidae	-	-	1	2	1	2
Criodrilidae	1	1	1	1	2	2
Glossoscolecidae	5	10	-	-	5	10
Lumbricidae	-	-	6	9	6	9
Megascolecidae	-	-	4	7	4	7
Ocnerodrilidae	1	4	-	-	1	4
Octochaetidae	-	-	1	2	1	2
Total	7	15	13	21	20	36

In this study, nine species are new records for Camaquã (Table 3). *Eukerria eiseniana* and *Eukerria saltensis* are reported for the first time for Rio Grande do Sul state and a new native genus and species is described as well.

Only 34 out of 497 total municipalities have been sampled (at least once) in Rio Grande do Sul so far. The samples from Camaquã are from few disturbed fields and adjacent areas, which suggest that the potential biodiversity of the entire state is high.

Much more work and sampling needs to be done to determine total earthworm diversity and to gain access to those species that may actually have a restricted distribution and/or are endangered due to their particular habitat requirements, behaviour and/or human pressure (James and Brown, 2006). The knowledge of biology and ecology of all species should also provide clues to sustainable soil management in agroecosystems or degraded soils.

Table 3. Present knowledge of earthworm diversity for Rio Grande do Sul, Brazil

Taxa	References
Family Acanthodrilidae	
Microscolex dubius (Fletcher, 1887)[1]	Lima & Rodríguez (this work)
Microscolex phosphoreus (Dugés, 1837)	Moreira (1903), Michaelsen (1927)
Family Criodrilidae	
Criodrilus laccum Hoffmeister, 1845	Knäpper & Porto, 1979
Guarani camaqua Rodríguez & Lima, 2006[3]	Lima & Rodríguez (this work)
Family Glossoscolecidae	
Alexidrilus litoralis Ljungström, 1972	Ljungström (1972)
Alexidrilus lourdesae Righi, 1971	Righi (1971a)
Glossodrilus parecis Righi & Ayres, 1975	Righi & Ayres (1975), Righi (1980)
Glossoscolex catharinensis Michaelsen, 1918	Righi (1974)
Glossoscolex grandis (Michaelsen, 1892)	Michaelsen (1892, 1918), Moreira (1903)
Glossoscolex truncatus Rosa, 1895	Michaelsen (1925)
Glossoscolex u. uruguayensis Cordero, 1943	Righi (1974)
Glossoscolex wiengreeni (Michaelsen, 1897)	Knäpper & Porto (1979)
Pontoscolex corethrurus (Müller, 1856)	Righi (1971a), Knäpper & Porto (1979)
Urobenus brasiliensis Benham, 1887	Michaelsen (1892), Üde (1893), Moreira (1903), Michaelsen (1918), Luederwaldt (1927), Righi (1971a,b,1985)
Family Lumbricidae	
Aporrectodea caliginosa (Savigny, 1826)	Moreira (1903), Righi (1967a), Knäpper & Porto (1979), Knäpper & Hauser (1969)
Aporrectodea rosea (Savigny, 1826)	Michaelsen (1892), Moreira (1903)
Aporrectodea trapezoide (Dugès, 1828)	Michaelsen (1892)
Bimastos parvus (Eisen, 1874)[1]	Černosvitov (1942), Righi (1968a), Lima & Rodríguez (this work)
Dendrobaena veneta (Rosa, 1886)	Knäpper & Porto (1979)
Eisenia foetida (Savigny, 1826)	Moreira (1903), Righi (1967a), Knäpper (1972a,b), Knäpper & Porto (1979)
Eisenia lucens (Waga, 1857)	Knäpper (1977), Knäpper & Porto (1979)
Eiseniella tetraedra (Savigny, 1826)	Pacheco *et al.* (1992)
Octolasion cyaneum (Savigny, 1826)	Righi (1967a)
Family Megascolecidae	
Amyntas corticis (Kinberg, 1867)	Knäper (1977), Knäpper & Porto (1979), Krabbe *et al.* (1993)
Amyntas gracilis (Kinberg, 1867)[1]	Michaelsen (1892, 1927), Righi & Knäpper (1965), Knäpper (1972ab), Knäpper & Porto (1979), Krabe *et al.* (1993), Lima & Rodríguez (this work)
Amyntas morrisi (Beddard, 1892)[1]	Righi & Knäpper (1965), Righi (1971b), Knäpper (1972a,b), Knäpper & Porto (1979), Krabbe *et al.,* (1993), Lima & Rodríguez (this work)
Metaphire californica (Kinberg, 1867)	Righi & Knäpper (1965), Knäpper & Porto (1979), Krabbe *et al.* (1993)
Metaphire schmardae (Horst, 1893)	Knäpper (1972a,b), knäpper & Porto (1979)
Polypheretima taprobanae (Beddard, 1892)	Righi & Knäpper (1965) Righi (1965, 1967b)
Pontodrilus litoralis (Grube, 1855)	Michaelsen (1900, 1910)
Family Ocnerodrilidae	
Eukerria eiseniana (Rosa, 1895)[2]	Lima & Rodríguez (this work)
Eukerria garmani (Rosa, 1895)[1]	Righi & Ayres (1975), Lima & Rodríguez (this work)
Eukerria saltensis (Beddard, 1895)[2]	Lima & Rodríguez (this work)
Eukerria stagnalis (Kinberg, 1867)[1]	Moreira (1903), Michaelsen (1927), Righi & Ayres (1975), Lima & Rodríguez (this work)
Family Octochaetidae	
Dichogaster annae (Horst, 1893)	Righi (1968b), Luederwaldt (1927)
Dichogaster saliens (Beddard, 1893)	Knäpper & Porto (1979)

[1] New record for Camaquã municipality
[2] New record for Rio Grande do Sul
[3] New genus and species

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Chapter 7

General discussion and concluding remarks

7.1. Introduction

This thesis was based on two methodological procedures to assess soil quality: qualitative (local knowledge) and quantitative (scientific knowledge). The two types of knowledge were reconciled. In so doing, I aimed to investigate the following problem: *"What basic measurements and procedures should we (as soil scientists co-operating with farmers) carry out, that will help us evaluate the effects of management on soil function now and in the future?"*. To address this problem, I assessed soil quality in the Camaquã region, Rio Grande do Sul state of Brazil. This region is known as one of the most important rice producing areas in Brazil and presents the most widely used rice management systems. Degradation of these soils is progressively getting worse due to intensive agricultural activity. Hence, the Camaquã region seemed particularly suited to illustrate the role of soil quality in soil assessment and management decisions.

Semi-structured interviews alternated with discussion groups were chosen as research methods in order to accurately assess farmers' knowledge at the individual and group level. Using this approach it was possible to identify if differences in soil quality perception occur between farmers who use different management systems. For the scientific approach, multivariate statistical analysis of 29 soil quality indicators was conducted through factor analysis and discriminant analysis in a novel way to arrive at a minimum data set (MDS) to assess soil quality. To evaluate three rice management systems, I made a comparison, in terms of soil functions, of soil quality indices based on 29 soil quality indicators; on 8 indicators selected from the 29 indicators that comprise the MDS; and on 4 indicators selected independently by farmers. I also studied the effects of the different rice management systems on physical and chemical soil quality. Finally, I reviewed the state of the knowledge on earthworm diversity in Rio Grande do Sul and described a new native criodrilid genus and species found in rice production systems.

7.2. Farmers' knowledge

A better understanding of the importance of farmers' knowledge of soil for the sustainability of farming systems is provided in chapter 2. Rice farmers from Camaquã were found to have detailed knowledge of the soil they are cultivating. They had a holistic view of soil quality based on dynamic processes, integrating chemical, physical and biological soil characteristics. Out of 11 soil quality indicators mentioned as "good" only soil colour, earthworms, soil organic matter and soil friability were considered "significant" by the farmers. A review of the state of the knowledge on earthworm diversity in Rio Grande do Sul (chapter 6) revealed 36 species and 20 genera, belonging to a total of 7 families in the state. With regard to the rice fields specifically, samples were taken and nine species were found in Camaquã (all new records for the region), two species were reported for the first time for the Rio Grande do Sul state and a new native genus and species of Criodrilidae (*Guarani camaqua*) was described. The majority of farmers (97%) identified earthworms as a good soil quality indicator but, nevertheless, the presence or absence of earthworms in the soil was not a key element in farmers' decision making, e.g., where to farm or buy land. A possible explanation is that they hardly see earthworms in their own fields because of the detrimental effects of management, particularly tillage, water management and pesticide use. Their management decisions rely more on soil indicators they can see and/or experience.

I also noted that from the four soil indicators considered as "significant", the farmers distinguished soil quality primarily on the basis of soil colour. According to their perceptions, the soil colour is mainly related to the clay content. Black soil is considered better because it contains more clay; it is commonly considered more fertile and consequently produces higher yields than white soil. Thus, they mainly evaluate the production potential of the soils according to soil texture, with soil colour as a proxy. Other studies have reported similar findings (Roming et al., 1996; Corbeels, et al., 2000; Barrios and Trejo, 2003; Desbiez et al., 2004).

7.3. Scientific approach: Minimum Data Set

Evaluation of soil quality is an active field of research in many countries and under many types of land use (Doran and Parkin, 1994, Brejda et al., 2000, Schipper and Sparling, 2000, Sparling and Schipper, 2004, Govaerts et al., 2006), among which is rice production

(Chaudhury et al., 2005). A lack of agreement on what constitutes good soil quality indicators, and also, how to obtain such indicators, underlines the need to minimize subjective choices and judgements.

I propose an approach for establishing a MDS of soil quality indicators (chapter 3), which is suitable to show not only human effects (as a result of management systems applied by farmers), but also differences due to inherent soil characteristics (soil texture classes).

Factor analysis was the first step to establish the MDS because it was an effective method to group or reduce the entire data set (29 soil indicators) into statistical factors (or principal components) for use in subsequent multivariate analysis, in this case discriminant analysis. From a data summarizing perspective, factor analysis provides the researcher with a clear understanding of which variables may act in concert and how many variables may actually be expected to have impacts in the analysis. Principal component analysis (PCA) was used as the method of factor extraction. Instead of working with all 29 soil indicators, I worked with the 25 soil indicators (from the 3 significant PCs) that had significant factor loadings (>0.4), in accordance with Sharma (1996) and Hair et al. (1998). I then used stepwise discriminant analysis (DA) to distinguish the most powerful PCs and, subsequently, the most powerful indicators from the selected PCs, both among management systems and soil texture classes. With these two steps I avoided arbitrary choices in selecting indicators within the significant PCs and DAs.

Using the distinction between textural class and management system I could see which PCs make a difference among the management systems and among soil textural classes (e.g., *"organic matter component")*, and which do not (e.g., *"acidity component"*). More specifically, I could observe that different indicators indicate different things. For example, earthworms, organic matter and mean weight diameter are important to discriminate between management systems, but not between soil textural classes. In contrast, bulk density, available water and Zn only discriminated between the soil textural classes. Some of the indicators (Cu and Mn) discriminated both between textural classes and management systems. Although textural class and management system were characterized by partly different sets of soil quality indicators, these indicators underlay the same 3 PCs. Had I not made a distinction between textural class and management system, I would not have been able to decide whether the soil indicators, which ended up in the MDS, would have been the consequence of inherent soil properties (i.c. texture) or management. Hence, I would not have been able to decide which soil indicators would be open to change as a result of changes in management.

The MDS consists of eight significant soil quality indicators: three physical (available water, bulk density and mean weight diameter), four chemical (organic matter, Zn, Cu and Mn) and one biological (earthworm number). Mn was the only indicator correlated with yield and at the same time discriminated among both management systems and soil textural classes. This suggests that the manganese status of the soils has a strong influence on rice production. The other seven indicators provide information on soil functioning which are interpretable by farmers. Sub-dividing samples according to texture led to arrive at a MDS which may provide an early warning tool to evaluate the sustainability of land use.

7.4. Scientific approach: Soil Quality Index

Using a MDS takes away the need for determining a large number of indicators to assess soil quality. However, due to the very complex nature of soil, involving the physical, chemical and biological indicators, and their interactions, the precision of soil quality assessment is increased by using as many indicators as possible. One way to solve this trade-off is to integrate information from soil indicators, and their relations to soil functions, into a soil quality index (SQI). A SQI helps to interpret data from different soil measurements and to show whether land use and management are sustainable.

I compared the outcomes of soil quality indices based on three sets of indicators: the entire data set (29 indicators), the MDS (8 out of the 29 indicators) and the farmers' indicator set (4 indicators chosen by farmers).

To calculate the SQI I used the SIMOQS (Sistema de Monitoramento da Qualidade do Solo) software using the model proposed by Karlen and Stott (1994), in view of three soil functions: (1) Water infiltration, storage and supply, (2) Nutrient storage, supply and cycling, (3) Sustain biological activity. All three soil functions were assumed to be equally important in the assessment. Indicators within the soil functions were assigned to different levels. Within each level, numerical weights were assigned to soil quality indicators based on their assumed importance to the particular soil function under consideration. To avoid assigning overweight to redundant, i.e. highly correlated indicators (r>0.80), they were separated in groups and their weights equally distributed.

Three types of standardized non-linear scoring functions typically used for soil quality assessment (Karlen et al., 1994, Hussain et al., 1999, Glover et al., 2000) can be generated: (1) “More is better”, (2) “Optimum” and (3) “Less is better”. The shape of the curves generated by the scoring curve equation is determined by critical values. Critical values include threshold and baseline values. Threshold and baseline values can be based on different sources: literature, specific data reference, expert opinion or measured values observed under near-ideal soil conditions for the specific site and crop (Burger and Karlen, 1999, Kelting et al., 1999). For chemical indicators the threshold and baseline values were based on the literature (see Manual, 2004). Because it was not possible to find a site that could be considered the natural soil condition in the region, in the case of biological and physical indicators threshold and baseline values were chosen from the collected dataset.

The results demonstrated that a few indicators (the 4 and 8 indicators sets) performed equally well as the entire data (29 indicators set), providing adequate information on soil quality differences among the management systems (chapter 4). I conclude that the soil quality index approach is appropriate for developing a quantitative procedure to evaluate the effects of rice management practices on soil quality. Software such as SIMOQS quickly identifies crucial soil indicators.

However, I agree with Sojka and Upchurch (1999) and Karlen et al. (2001) that there is no ideal or magic index value. Identifying critical functions and selecting appropriate indicators in the process of developing soil quality indices, has to be flexible according to users’ needs. In view of appropriate use of SQIs it is necessary to understand the underlying relationships between indicators and soil functions. Much scientific work is still needed to substantiate thresholds, baselines and optimum values of indicators to enhance the reliability of SQIs and, hence, their usefulness for management decisions.

7.5. Scientific approach: differences in physical and chemical properties as a result of management

The value of the soils in the Camaquã region partly resides in combining the production of rice with other crops. However, the level of soil degradation has become an obstacle for growing deeper rooting crops such as maize, soybean or sorghum in rotation with flooded rice (Lima et al., 2002). Wet tillage in rice can destroy soil structure and creates a poor physical condition for the following crop (Tripathi et al., 2005, Mohanty et al., 2006). Degradation of the regional soils is mainly related to high soil density, low porosity, high micro-/macropore ratio, reduced hydraulic conductivity, and low water infiltration rate. It is progressively worsening because of the intensity of tillage applied in rice production (Pauletto et al., 2004). Special attention to the impact of the rice management systems in affecting soil physical and chemical quality was therefore warranted (chapter 5). The analysis revealed that soil physical and chemical properties (as expected) were affected by clay content, but after statistically eliminating the natural variability of clay content, I found that management practices adopted by farmers also have an impact on the physical and chemical soil quality.

The results showed a particular, relevant characteristic of the regional lowland soils. The deficient drainage caused by a dense and impervious B horizon leads to undesirable conditions (too wet) during periods of soil preparation, sowing and harvest, even during periods when the irrigation water is removed from the field because of rainfall. This situation most probably is one of the explanations why differences in bulk density, were associated to microporosity and not to macroporosity. A reduced microporosity indicates a reduction of soil structural quality which is difficult to reverse. As the sampling was done immediately after harvest, the analysis showed the long-term detrimental effect of tillage under adverse conditions (and not the short-term tillage effect which typically is an increase in macroporosity).

Considering the above, the results indicate that the semi-direct management system retains better (sustainable) soil conditions, whereas the pre-germinated and conventional systems appear to contribute to the degradation. I may affirm that the soils studied are suitable for irrigated rice production and soil degradation has not yet been an obstacle to obtain high rice yields. However, physical degradation may well underlie the difficulty farmers experience in growing other crops than rice in the region.

7.6. Concluding remarks

I set out this study with the following problem statement: *"What basic measurements and procedures should we (as soil scientists co-operating with farmers) carry out, that will help us evaluate the effects of management on soil function now and in the future?"*. I have been able to distinguish between inherent, i.e. soil type-related, and management-related effects, which is an important step in operationalizing soil quality.

The study has increased the understanding of the complex nature of soil using an integrated approach. It shows a way towards identifying the procedures to arrive at soil quality indicators, which can be applied to monitor soil quality of rice fields and support management decisions.

At a specific level, the findings highlight the need of more investigation on the impact of rice management systems on micronutrients, especially on Mn availability in the regional soils. Also, I found 9 out of 36 earthworm species from Rio Grande do Sul in the investigated rice fields, of which one was new to science. This result suggests that more work needs to be done to determine the total earthworm diversity. Knowledge of the biology and ecology of earthworm species may provide clues to sustainable soil management in rice and also in other agroecosystems.

From a scientific point of view, the semi-direct rice management system showed better soil quality than the other management systems. Although socio-economic issues are key driving forces in adopting a certain management system and crop rotation, farmers recognize that management practices, in association with inherent soil characteristics, have a strong effect on soil quality (Chapter 2). Hence, the soil quality assessments (MDS and SQI) were successful in reconciling farmers' and scientific knowledge.

A dynamic assessment will be necessary for determining the direction and magnitude of changes, so as to assess whether the soil is being sustained, degraded or aggraded. To validate the approach proposed in this study, further research is needed on soil quality evaluation in different regions, under different managements and land uses over time.

The results indicate that without both local and scientific knowledge a satisfactory level of crop production and the maintenance of soil quality cannot be achieved at the same time. Therefore, researchers must continue to face the challenge to provide a base for bridge-building between farmers' and scientists' knowledge. Reconciling local and scientific knowledge is one of the most important steps towards evaluating the feasibility of alternative production systems and the sustainability of land use in terms of long-term soil quality.

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Summary

Introduction

In the state of Rio Grande do Sul, Brazil, rice production is one of the most important regional activities. Rice production is located mainly in the southern lowlands where approximately 5.5 million tons of rice per year are produced, equivalent to 52% of total Brazilian rice production. There is a growing concern with farmers that the land use practices in rice production systems in the Camaquã region may not be sustainable because of detrimental effects on soil quality. Therefore, the problem statement was formulated as:

What basic measurements and procedures should we (as soil scientists co-operating with farmers) carry out, that will help us evaluate the effects of management on soil function now and in the future?

In order to answer this question, the research leading to this thesis was based on two methodological procedures to assess soil quality: qualitative (local knowledge) and quantitative (scientific knowledge). These two methods were used to accomplish the following objectives: (1) To understand and describe how rice farmers assess soil quality; (2) To propose a minimum data set to assess soil quality; (3) To establish which soil quality indicator(s) can be managed in view of sustained production; and (4) To reconcile local and scientific knowledge.

The selection of the study area was based on the fact that farmers use three main management systems for irrigated rice in Rio Grande do Sul: conventional (dry seedbed preparation and sowing, high tillage intensity), semi-direct (dry seedbed preparation and sowing, low tillage intensity), and pre-germinated (seedbed preparation and sowing on inundated fields, high tillage intensity). There is a large variation of farm sizes (2-500 ha) in the region. Local knowledge was assessed at the farmer's house or in his/her field. Thirty two rice farmers, representing the various farm sizes and management systems, were interviewed. For the scientific approach 21 rice fields on different soil great groups and under different rice management systems were selected. In each field, five replicate plots were randomly laid out within an area of 3 ha. In total 105 representative plots were sampled. These samples were bulked and mixed for the analysis of 29 physical, chemical and (micro)biological soil properties. In addition to the soil samples, all mature rice plants were manually harvested from each plot area.

Local knowledge

In a study set up for understanding soil quality from a rice farmers' perspective, at the individual and group level, semi-structured interviews alternated with group discussions were chosen as research methods. Rice farmers from Camaquã were found to have detailed knowledge of the soil they are cultivating. They had a holistic view of soil quality based on dynamic processes, integrating chemical, physical and biological soil characteristics. The study revealed that farmers' perceptions of regional soil quality were closely related to visible environmental and economic factors. Eleven indicators were mentioned as good soil quality indicators: earthworms, soil colour, yield, spontaneous vegetation, soil organic matter, root development, soil friability, rice plant development, colour of the rice plant, number of rice tillers and health of the cattle (grazing on the fields after harvest). Out of these 11 soil quality indicators only soil colour, earthworms, soil organic matter and soil friability were considered "significant" by the farmers, while three indicators were found to be useful in farmers' decision-making: spontaneous vegetation, rice plant development and soil colour.

Scientific approach

In order to assess soil quality following a scientific approach, a minimum data set (MDS) based upon the 29 indicators collected was established in a novel way. For this purpose factor analysis and discriminant analysis were used as statistical tools. The MDS consists of eight significant soil quality indicators: three physical (available water, bulk density and mean weight diameter), four chemical (organic matter, Zn, Cu and Mn) and one biological (earthworm number).

In order to define the usefulness of this scientific approach, and to compare this with the local knowledge, a soil quality index (SQI) was determined in three ways: (a) based on the entire data set of 29 indicators, (b) based on the MDS containing 8 out of the 29 indicators, and (c) based on the farmers' indicators set of 4 indicators. This study demonstrated that soil quality as a result of the management systems was best assessed when using the entire 29 indicators set. However, the 8 and 4 indicators sets performed almost equally well as the 29 indicators set in showing the same trends in differences between management systems, soil textural classes and soil functions. The index values indicated that the semi-direct management system resulted in the highest overall soil quality, followed by the pre-germinated and conventional systems. The SQI approach is appropriate for developing a quantitative procedure to evaluate the effects of rice management practices, providing meaningful information on soil quality for land management decisions.

Degradation of the regional soils is mainly related to high soil bulk density, low porosity and low water infiltration rate and it is progressively worsening because of the intensity of tillage applied in rice production. This degradation has been an obstacle to establish other crops in rotation with flooded rice. Thus, a further study was undertaken to assess the effects of the different rice management systems on the physical and chemical soil quality. The results also indicate that the semi-direct management system retains better soil conditions (i.e. is more sustainable) than the pre-germinated and conventional systems, which appear to contribute to soil degradation. The soils studied are suitable for irrigated rice production and soil degradation has not yet been an obstacle to obtain high rice yields. However, physical degradation will lead to difficulties of growing crops other than rice in the region.

The earthworm number (as one of the biological indicators) was assessed in the rice fields of Camaquã. Nine species were found (all new records for the region), two species were reported for the first time for the Rio Grande do Sul state and a new native genus and species of Criodrilidae (*Guarani camaqua*) was described. Finally, a review of the state of knowledge on earthworm diversity in Rio Grande do Sul revealed 36 species and 20 genera, belonging to a total of 7 families in the state.

Concluding remarks

The main conclusion to be drawn from this study is that it has increased the understanding of the complex nature of soil using an integrated approach. It has identified statistical procedures to arrive at soil quality indicators, which can be applied to monitor soil quality of rice fields and to support management decisions.

The soil quality assessments (MDS and SQI) were successful in reconciling farmers' and scientific knowledge, but a dynamic assessment (over time) will be necessary for determining the direction and magnitude of changes, allowing assessment of whether the soil quality is sustained, degrading or improving. Further research is needed to determine if this method of soil quality evaluation is applicable in different regions, under different land use and management systems.

Samenvatting

Introductie

De verbouw van rijst is een van de belangrijkste landbouw activiteiten in de zuidelijke Braziliaanse staat Rio Grande do Sul. De rijst productie komt voornamelijk voor in de zuidelijke laaggelegen gebieden. Hier wordt jaarlijks 5.5 miljoen ton rijst geproduceerd, wat neerkomt op ongeveer 52% van de totale Braziliaanse rijstproductie. In een van de belangrijke regio's, Camaquã, groeit de zorg onder de boeren wat betreft de duurzaamheid van het landgebruik, als gevolg van de negatieve effecten op de kwaliteit van de bodem.

Gezien deze zorg, is in het voorliggende proefschrift getracht een antwoord te vinden op de volgende vraagstelling:

Welke metingen en activiteiten zouden wij, (bodemkundigen samenwerkend met boeren), moeten toepassen zodat we (op dit moment maar ook in de toekomst) de gevolgen van bewerking en gebruik van de grond op de kwaliteit van de grond kunnen bepalen?

Het onderzoek wat nodig werd geacht om deze vraag te kunnen beantwoorden, is gebaseerd op twee methoden om de kwaliteit van de bodem te kunnen bepalen: een kwalitatieve benadering (lokale kennis van de boeren) en een kwantitatieve benadering (wetenschappelijk). Deze twee benaderingen werden gebruikt om de volgende doelstellingen te kunnen behalen:

(1) Het begrijpen en beschrijven van de manier waarop rijst verbouwers de kwaliteit van de bodem beoordelen; (2) Het ontwikkelen van een zo klein mogelijke set gegevens om de bodemkwaliteit te kunnen beoordelen; (3) Het kunnen bepalen welke bodemkwaliteits kenmerk kan worden beïnvloed om tot een duurzame productie te kunnen komen; en (4) Het koppelen van lokale en wetenschappelijke kennis.

De keuze van de regio waar de studie is uitgevoerd is gebaseerd op het feit dat er voor rijst in Rio Grande do Sul drie productiesystemen kunnen worden onderscheiden: "conventioneel" (het maken van het zaaibed en de inzaai gebeuren in droge grond, er is een hoge intensiteit van grondbewerking); "semi-direct" (als conventioneel, maar met een lagere intensiteit van grondbewerking) en "pre-germinated" (waarbij zowel het maken van het zaaibed, als de inzaai van de rijst (met voorgekiemde rijstkorrels) wordt uitgevoerd op de onder water staande velden met een hoge intensiteit van grondbewerking). In Camaquã worden deze drie systemen gebruikt. Er is hier een ruime variatie van groottes van de bedrijven (2 tot 500 ha).

De lokale kennis werd beoordeeld bij de boeren zelf, op hun bedrijf. Een totaal van 32 boeren, die de verschillende bedrijfsgroottes en productiesystemen vertegenwoordigen, zijn geïnterviewd. Voor de wetenschappelijke benadering werden 21 velden geselecteerd, alle te vinden op verschillende grondsoorten ("great groups") en in gebruik onder de verschillende productiesystemen. In elk veld werden (binnen een standaardgrootte van 3 ha) plots in vijf herhalingen aangelegd op willekeurige plaatsen. Op deze manier werden 105 representatieve plots bemonsterd. Bodemmonsters op deze plots verzameld, werden geanalyseerd op een totaal van 29 fysische, chemische en (micro)biologische kenmerken. Ook werd op deze plots de rijst met de hand geoogst voor analyse.

Lokale kennis

Om te begrijpen hoe de rijstboeren omgaan met bodemkwaliteit, werd een studie uitgevoerd bij zowel individuele boeren als groepen. Boeren werden ondervraagd over hun inzichten en er werden groepsdiscussies georganiseerd. Het bleek dat de rijstboeren in Camaquã een gedetailleerde kennis hebben van hun velden en de bodem waarop zij rijst verbouwen. Bij de beoordeling van bodemkwaliteit volgen zij een holistische benadering, gebaseerd op zichtbare, dynamische processen waarbij chemische, fysische en biologische bodemeigenschappen worden geïntegreerd.

Hun perceptie van kwaliteit is nauw verbonden met economische en milieu factoren. In totaal werden 11 indicatoren genoemd die kenmerkend zijn voor een goede bodemkwaliteit: aanwezigheid van regenwormen, kleur van de grond, opbrengst van het gewas, "spontane vegetatie" (dit kan onkruid zijn, maar ook nuttige vegetatie anders dan het gewas), organische stof in de bodem, wortelontwikkeling van de rijst, verkruimelbaarheid van de grond, ontwikkeling van het gewas, kleur van de rijstplant, mate van uitstoeling van de rijstplant, en de gezondheidstoestand van het vee dat op de rijststoppel graast. Uit deze 11 indicatoren werden door de boeren alleen kleur van de grond, regenwormen, organische stof en verkruimelbaarheid als 'significant' beschouwd. De indicatoren spontane vegetatie, ontwikkeling van het gewas en kleur van de grond, beschouwden de boeren als "nuttig voor besluitvorming" (o.a. voor de keuze van het productiesysteem).

Wetenschappelijke benadering

Bij de wetenschappelijke benadering van bodemkwaliteit is een minimum dataset (MDS) ontwikkeld, uitgaande van de 29 verzamelde en geanalyseerde kenmerken. Hiertoe is op een nieuwe manier gebruik gemaakt van statistische methoden: factor analyse en discriminante analyse. De aldus bepaalde MDS bevat 8 significante bodemkwaliteitsindicatoren; drie fysische (beschikbaar water, bulkdichtheid, en gemiddelde gewogen aggregaatdiameter), vier chemische (organische stof, Zn, Cu en Mn), en één biologische (aantal regenwormen).

Teneinde het nut van deze wetenschappelijke benadering te bepalen, en deze met de lokale kennis te vergelijken, werd een bodemkwaliteitsindex (SQI) berekend op drie verschillende manieren: (a) gebruik makend van de volledige dataset van 29 indicatoren, (b) gebruik makend van de MDS, dus met 8 van de 29 indicatoren, en (c) gebruik makend van de 4 door de boeren significant geachte indicatoren. Deze studie toonde aan dat bodemkwaliteit als gevolg van het toegepaste productiesysteem het best kon worden beoordeeld door alle 29 indicatoren te gebruiken. Ook de kleinere sets van 8 en 4 indicatoren gaven goede resultaten en toonden dezelfde trends aan wat betreft verschillen tussen productiesystemen, bodem textuur klassen, en bodemgebruiksfuncties. De index waarden toonden aan dat het “semi-direct” productiesysteem leidde tot de beste algemene bodemkwaliteit, gevolgd door “pre-germinated” en conventioneel. Deze index benadering is goed geschikt om een kwantitatieve procedure te ontwikkelen om de effecten van werkmethoden bij de teelt van rijst te evalueren. Deze informatie over de bodemkwaliteit kan vervolgens als uitgangspunt dienen bij de keuze van landgebruiks- en productiesystemen.

De degradatie van de bodems in de Camaquã regio is met name te wijten aan een hoge bulkdichtheid, en (als gevolg daarvan) een geringe porositeit en een geringe infiltratiecapaciteit. Deze verslechtering van de structuur lijkt vooral versterkt te worden door de intensiteit van de grondbewerking in de rijstteelt, en veroorzaakt problemen bij de inzaai en opkomst van andere gewassen naast (in rotatie met) natte rijst. Deze veronderstelling is getoetst in een studie naar de effecten van de rijstproductiesystemen op de fysische en chemische bodemkwaliteit. De resultaten van deze studie bevestigen dat onder het “semi-direct” systeem de bodemstructuur beter behouden blijft (dus meer duurzaam is) dan onder de andere systemen, die tot degradatie leiden. Hoewel de bodems zeer geschikt zijn voor rijstteelt, en opbrengsten nog niet lager worden, kan degradatie van de structuur een probleem worden als besloten wordt andere gewassen te gaan telen.

Wat betreft de biologische indicatoren, is er een studie gedaan naar de regenwormen in de rijstvelden in Camaquã. Negen soorten zijn gevonden (alle voor het eerst gerapporteerd in de regio), twee soorten werden voor het eerst aangetroffen in de staat Rio Grande do Sul, en een nieuw inheems geslacht van de soort Criodrilidae *(Guarani camaqua)* is beschreven. Uit deze studie bleek ook dat de huidige diversiteit aan regenwormen in de staat een totaal van 36 soorten en 20 geslachten telt, behorende tot 7 families.

Conclusies

De studie heeft aangetoond dat door een geïntegreerde benadering de complexe aard en samenstelling van de bodem beter begrepen kan worden. Statistische methoden en procedures die in het kader van deze studie ontwikkeld zijn maken het mogelijk om bodemkwaliteits indicatoren te vinden die toegepast kunnen worden om de kwaliteit van rijstvelden te kunnen volgen en die kunnen helpen in de keuze van productie- en gebruikssystemen.

Hoewel MDS en SQI voor de evaluatie van bodemkwaliteits succesvol waren door de koppeling van lokale kennis van boeren met resultaten van wetenschappelijk onderzoek, zal een dynamische evaluatie nodig zijn om richting en grootte van veranderingen te kunnen bepalen. Hierdoor kan beoordeeld worden of een bepaald systeem de bodemkwaliteit verbetert of verslechtert.

Tenslotte is verder onderzoek nodig om vast te stellen of de in dit proefschrift beschreven methodes van bodemkwaliteitsbeoordeling toepasbaar zijn in andere regio’s, en bij andere land- en bodemgebruikssystemen.

Resumo

No estado do Rio Grande do Sul a produção de arroz é uma das mais importantes atividades agrícola. Esta atividade está localizada principalmente nas zonas de terras baixas da metade Sul do Estado. Aproximadamente 5.5 milhões de toneladas são produzidas, equivalente a 52% to total da produção brasileira. Além da importância econômica, esta atividade é também importante para o sustento de muitos agricultures que estão cada vez mais preocupados com os efeitos das práticas agrícolas na qualidade dos seus solos. De fato, os agricultores estão conscientes que suas práticas de uso da terra podem não ser sustentáveis por causa dos efeitos detrimentais que elas geram na qualidade do solo. Diante desta situação, e com o intúito de investigar este fenômeno formulou-se a seguinte questão de pesquisa:

Que medidas básicas e procedimentos são necessários para avaliar os efeitos do manejo nas funções do solo, considerando-se o conhecimento científico e dos agricultures?

Para responder esta questão utilizou-se dois procedimentos metodológicos: qualitativo (conhecimento local) e quantitativo (conhecimento científico). Estes dois métodos foram usados para contemplar os seguintes objetivos: (1) entender e descrever como os agricultores de arroz avaliam a qualidade do solo; (2) propor um mínimo de indicadores para avaliar a qualidade do solo; (3) estabelecer quais indicadores da qualidade do solo podem ser manejados em vista da produção sustentável; e (4) reconciliar o conhecimento local e científico.

A área de estudo selecionada localiza-se no município de Camaquã, cerca de 150 km ao Sul da Capital do Estado. A escolha desta região deve-se ao fato dos agricultores usarem os três principais sistemas de manejo de arroz irrigado no Rio Grande do Sul: convencional (preparação do solo e semeadura sob solo seco, manejo de alta intensidade), semi-direto (preparaçã do solo e semeadura sob solo seco, manejo de baixa intensidade) e pré-germinado (preparação do solo e semeadura sob solo inundado, manejo de alta intensidade). Na região há uma grande variação de tamanhos de lavouras (2-500 ha). Trinta e dois agricultores, representando os diversos tamanhos das lavouras e sistemas de manejo, foram entrevistados. Para o enfoque quantitativo (conhecimento científico), foram selecionadas 21 lavouras com diferentes solos e com diferentes sistemas de manejo. Em cada lavoura, cinco locais de coleta foram identificados dentro de uma área central de 3 ha. No total 105 áreas foram amostradas. As amostras de solo após retiradas destas áreas, quando necessárias foram misturadas e, então

enviadas para análise laboratorial de 29 propriedades fisicas, químicas e (micro)biológicas do solo. Em adição, coletou-se amostras da produção de arroz de cada área onde o solo foi coletado.

Conhecimento local (qualitativo)

Para entender a qualidade do solo a partir da perspectiva dos agricultores utilizou-se entrevistas semi-estruturadas alternadas com discussões de grupo. Os agricultores de Camaquã mostraram ter um conhecimento detalhado do solo que eles cultivam. Eles tem uma visão holística da qualidade do solo baseada na experiência que integra características químicas, físicas e biológicas do solo. O estudo revelou que a percepção dos agricultores sobre a qualidade do solo está relacionada com fatores ambientais visíveis e econômicos. Onze indicadores foram mencionados como bons indicadores da qualidade do solo: minhoca, cor do solo, produção, vegetação espontânea, matéria orgânica, desenvolvimento da raiz, terra fofa, desenvolvimento da planta do arroz, cor da planta do arroz, número de perfilhos e saúde do animal (pastando nos campos após a colheita). Dos 11 indicadores a cor do solo, a presença de minhocas, a matéria orgânica e a terra fofa foram considerados “significantes” pelos agricultores para monitorar a qualidade do solo. Porém, somente três indicadores foram identificados como úteis para a tomada de decisão do dia-a-dia: vegetação espontânea, desenvolvimento da planta do arroz e a cor do solo.

Conhecimento científico (quantitativo)

Para avaliar a qualidade do solo de forma quantitativa, foi estabelecido um conjunto mínimo de indicadores (MDS) a partir dos 29 indicadores inicialmente coletados. Para construir o MDS utilizou-se da Análise Fatorial e da Análise Discriminante, as quais foram importantes para reduzir os 29 indicadores em apenas oito indicadores que são indispensáveis para acessar a qualidade do solo de arroz. Destes, três são físicos (água disponível, densidade do solo e diâmetro médio ponderado), quatro são químicos (matéria orgânica, Zn, Cu e Mn) e um é biológico (minhoca).

Para definir a utilidade da perspectiva quantitativa, bem como para compará-la com o conhecimento local propôs-se o estabelecimento de um índice da qualidade do solo (SQI). O SQI foi determinado de três formas: (a) baseado nos 29 indicadores; (b) baseado no MDS contendo 8 dos 29 indicadores; e (c) baseado nos 4 indicadores propostos pelos agricultores para monitorar a qualidade do solo. Este estudo demonstrou que a qualidade do solo é melhor avaliada quando usou-se o conjunto inteiro dos 29 indicadores. Entretanto, a média dos SQI's resultantes do MDS (8 indicadores) e dos 4 indicadores propostos pelos agricultores, não foi muito diferente daquela obtida via o uso dos 29 indicadores. Além do mais, as três formas de cálculo mostraram tendências similares na diferenciação de sistemas de manejo, classes texturais e funções do solo. Para as três formas de cálculo, o sistema de manejo semi-direto apresentou o maior índice de qualidade, seguido pelo sistema pré-germinado e convencinonal. Concluí-se que o SQI é um instrumento apropriado para quantificar e avaliar os efeitos das práticas de manejo sob a qualidade do solo.

A degradação dos solos de terras baixas está relacionada principalmente a alta densidade do solo, baixa porosidade e baixa infiltração da água. Este problema é progressivamente piorado pela intensiva produção de arroz. Esta degradação tem sido um obstáculo para estabelecer outras culturas em rotação com arroz irrigado, o que nos motivou a estudar os efeitos dos diferentes sistemas de manejo na qualidade física e química do solo. Os resultados também indicaram que o sistema de manejo semi-direto apresenta melhores condições do solo (i.e. é mais sustentável) do que os sistemas pré-germinado e convencional. Embora, os solos de terras baixas são naturalmente adequados para a produção de arroz irrigado, a contínua degradação física impõe crescente limitações para a implantação de outras culturas em terras baixas.

O último estudo feito foi com minhocas (considerado como um indicador biológico). O número e diversidade de minhocas foram avaliados nas lavouras de arroz, algo não muito frequente na comunidade científica regional. Nove espécies foram encontradas (todas novos recordes para a região de Camaquã), duas espécies foram reportadas pela primeira vez para o estado do Rio Grande do Sul e uma nova espécie e gênero de Criodrilidae (*Guarani camaqua*) foi descrita. Finalmente, uma revisão do estado do conhecimento sobre a diversidade de minhocas no Rio Grande do Sul revelou que 36 espécies e 20 gêneros pertencentes a 7 famílias são conhecidas até o momento no estado.

Conclusão

Salienta-se como conclusão que as abordagens quantitativa e qualitativa quando usadas de forma integrada contribuem para o entendimento da natureza complexa do solo. Neste estudo foram identificados procedimentos estatísticos para selecionar os indicadores que podem ser aplicados para monitorar a qualidade do solo nas lavouras de arroz e ajudar nas tomadas de decisão dos produtores.

Os procedimentos propostos para a avaliação da qualidade do solo (MDS e SQI) foram eficazes no sentido de considerar tanto o conhecimento dos agricultores locais quanto o conhecimento científico. No entanto, uma avaliação dinâmica (através do tempo) será necessária para a determinação da direção e magnitude das mudanças, a qual permitirá avaliar se o solo está sendo manejado de forma sustentável ou se está sendo degradado. Futuras pesquisas são necessárias para determinar se este método de avaliação da qualidade do solo é aplicável em diferentes regiões, sob diferentes usos da terra e sistemas de manejo.

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With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

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Writing of Project Proposal (5 credits)
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Laboratory Training and Working Visits (2 credits)
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- Research methodology: designing and conducting a PhD research project; MGS (2003)
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- II Earthworm taxonomy course; EMBRAPA-Londrina, Brazil (2004)
- Principles and techniques in ecological agriculture; EMBRAPA-Rio de Janeiro, Brazil (2004)
- Basic statistics; PE&RC (2004)

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- Two oral and two poster presentations at WCSS (World Congress of Soil Science), USA (2006)
- One poster presentation at ISTRO (International Soil Tillage Research Organization), Germany (2006)
- One poster presentation at ISEE (International Symposium on Earthworm Ecology), Poland (2006)
- One poster presentation at CBCS (Brazilian Congress of Soil Science), Brazil (2007)