Forages for Soil Improvement in Uruguayan Cropping Systems

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

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FACULTY OF GRADUATE STUDIES

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ABSTRACT

Gentile, Roberta M. M.Sc., The University of Manitoba, September, 2002. Forages for Soil Improvement in Uruguayan Cropping Systems. Major Professor; Martin H. Entz.

Grain crops are grown in Uruguay in a mixed cropping system that rotates several years of annual grain crops with several years of forage crops as pasture. In some areas of South America the amount of pasture is decreasing in favour of no-till annual crop production. However, forages may play an important role in soil amelioration during the pasture phases of the mixed cropping system, and improve soil structure for grain crop production. This thesis was undertaken to determine the role of forage crops in improving soil conditions by examining (1) the root distributions of forages, (2) the changes made to soil physical properties by forages, and (3) the soil organic carbon allocation of forages. All experiments were conducted on a silty clay loam soil (Oxyaquic Argiudoll) at the INIA La Estanzuela research station in southwestern Uruguay (34°20'S, 57°41'W).

The root characterization of tall fescue (*Festuca arundinacea* Schreb.), alfalfa (*Medicago sativa* L.), and chicory (*Cichorium intybus* L.) showed that all species were able to penetrate to greater than 1 m of the soil profile. The three species differed in their root count and root biomass distributions, as reflective of differences in the root type and branching of the species. Tall fescue exemplified a fibrous root system with high root counts and small root biomass per count ratios throughout the profile, whereas alfalfa and chicory are representative of taproot systems containing fewer root counts and large root biomass per count ratios.

The improvement of soil physical properties and enhancement of following grain crop production of tall fescue, alfalfa, and chicory was not clearly evident due to limitations of the experiment from weed and climate conditions. Early growth of a grain sorghum (*Sorghum bicolor* (L.) Moench.) test crop following the forages was greater after alfalfa and chicory. Few changes were seen in the soil physical properties with chicory reducing soil strength at a 20 cm depth under high soil moisture conditions. Due to the weed complications during the experiment, the biological tillage of forages in Uruguay requires further study.

The soil organic carbon allocation of forages was assessed in two experiments of different time duration. Physical size fractionation procedures were used to separate total organic carbon into three carbon pools. After a 7 yr experiment with different forage species, soil organic carbon was only increased in the coarse particulate fraction in the surface 7.5 cm, as compared to an annual crop rotation. A 38 yr crop rotation experiment showed that including pasture in rotation with annual crops increased soil organic carbon significantly in all carbon fractions at depths of 20-40 and 40-60 cm. The long-term crop rotation study shows that incorporating forage crops in cropping systems can contribute to carbon sequestration in these soils.

1. INTRODUCTION

Forage crops are a principal component of the mixed cropping system practiced in southwestern Uruguay. The practice of rotating 3-4 yr of annual grain crops with 3-4 yr of pasture evolved from a need to protect the soil from erosion processes. The advent of no-till cropping practices in Argentina and Uruguay has seen the area under pasture decrease in recent years in favour of cash crop production (Studdert et al., 1997; Díaz-Zorita et al., 2002). It is believed that no-till practices can confer the same soil conservation benefits for annual crop production as including forages in rotations, but they may decrease crop yields or increase soil compaction in some areas (Ferreras et al., 2000). The importance of forage crops in maintaining and improving soil structure in mixed cropping systems needs to be recognized, if their significance in crop rotations can be valued in comparison to grain crops.

There is also renewed interest in the use of forage crops because of their potential to sequester carbon and help mitigate climate change. Agricultural soils can act as a sink for carbon through the addition of organic matter and incorporating forages into crop rotations is one of the management practices that can increase organic matter levels. Policy makers are exploring the option of designing a carbon credit trading system, and the possibility exists that carbon sequestration may be a new source of income for farmers.

Perennial forage crops have a large potential for improving soil structure or sequestering carbon because of the growth and continuity of their root systems over several years, and a lack of tillage. The actions of plant roots can perform biological tillage and ameliorate the soil by natural means, and roots are an important source of plant carbon additions to the soil.

The intent of this study was to evaluate the rotational benefits of forage crops on soil structure and carbon sequestration. Given that these actions are primarily influenced by root activity, this thesis had the following objectives:

(1) To observe and characterize the root systems of forage species in Uruguay.

(2) To determine what improvements are made to soil physical properties by these forage species, and how this affects the growth of a following grain crop.

(3) To evaluate the role of forage crops in carbon sequestration.

2. LITERATURE REVIEW

2.1 Cropping Systems in Uruguay

Agriculture in Uruguay is dominated by cattle production and it is an element that permeates Uruguayan culture. The majority of the country's land base is devoted to beef and sheep production on natural rangeland or permanent pasture. The southwestern portion of the country is the main grain crop and dairy production region. The INIA La Estanzuela research station (34°20'S, 57°41'W) is found within this region. Uruguay is located in a humid, temperate climate zone. Mean monthly precipitation and temperatures for the research station are listed in Appendix A. The southwestern corner of the country is also characterized by heavy textured soils and rolling hills with 2-4% slopes.

When the country was first cultivated by European immigrants they used cropping practices that involved extensive use of tillage and fallow. These practices, combined with the soil and climate characteristics of the region, lead to soil erosion and a loss of productivity (Martino, 1994). To combat the problem of soil erosion, farmers adopted a mixed cropping system that rotates annual grain crops with pastures. Under this arable-pasture system, about 0.5 million ha of annual grain crops are grown each year. The selection of crops grown includes corn (*Zea mays* L.), sorghum (*Sorghum bicolor* (L.) Moench.), sunflower (*Helianthus annuus* L.) and soybean (*Glycine max* (L.) Merrill) during the summer season (October-April), and wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and oats (*Avena sativa* L.) during the winter season (June-December). The winter season cereal crops often serve a dual purpose for grain and forage production. Pastures are a mixture of perennial grasses and legumes dominated by tall fescue (*Festuca arundinacea* Schreb.), birdsfoot trefoil (*Lotus corniculatus* L.) and clovers (*Trifolium* spp.).

Similar mixed cropping systems with rotations of annual crops and pasture are also practiced in the Pampas of Argentina and in New Zealand. The length of each phase of the rotation is determined by profitability, persistence of the forage species, and the need to maintain soil structure (Francis et al., 1999). Soil fertility, structure and organic matter have been observed to decrease during the cropping phases and increase during the pasture phases of a mixed system (Haynes et al., 1991; Díaz, 1992; Studdert et al., 1997; Francis et al., 1999; Díaz-Zorita et al., 2002).

During the last ten years or so, there has been a shift in the land use in the Argentine Pampas and a few areas in Uruguay. The area under pasture has decreased, while the area under crop production, and predominantly summer annuals, has increased (Viglizzo et al., 1995; Studdert et al., 1997). This increase in annual crop production coincides with the introduction of no-till farming practices in the region (Díaz-Zorita et al., 2002). The adoption of no-till practices is believed to confer the same soil conservation benefits as including pasture phases in crop rotations, and has seen the decline of pastures in favour of cash crops. The move to increased crop production can be viewed as a departure from sustainable long-term agriculture production as the agriculture system becomes more dependent on fossil fuels and inputs such as nitrogen fertilizer (Viglizzo et al., 1995).

No-till production in this region has not always been beneficial for crop production, as some yields of corn and wheat have been reported to decline with no-till practices (Taboada et al., 1998; Ferreras et al., 2000). These yield decreases are attributed to increased soil compaction under no-till, which limits root growth and therefore influences crop production, at least in the short-term. Soil compaction, or mechanical impedance to root growth, is one of the major constraints for the adoption of no-till practices in this region, at least in the short-term transition phase from a poorly structured, tilled soil (Martino, 1998; Ferreras et al., 2000).

Martino (1998) recommend that the use of biological tillage, by the action of plant roots, be studied in this system as a measure to decrease soil compaction and improve crop productivity. Previous work has shown that soil compaction may be alleviated by natural means. A 2 or 3 yr pasture has been shown to reduce soil compaction, improve soil structure, and increase grain crop yields (Alakukku, 1998; Radford et al., 2001).

2.2 Biological Tillage

Biological tillage refers to the improvement of soil structure by biological means such as the action of plant roots, earthworms and other soil organisms. Plant roots may naturally ameliorate the soil by physically binding and stabilizing aggregates, releasing exudate compounds that bind aggregates, and creating channels in the soil (Dexter, 1991; Bathke et al., 1992). These channels, referred to as biopores, remain after the roots decompose and can serve as paths of low resistance for following root growth or water movement. These pores can also resist closing under compaction stresses, especially if vertically oriented (Blackwell et al., 1990). Controlling biological tillage processes through management practices may be a very cost effective way to alleviate soil structural problems (Dexter, 1991).

Biopores made by earthworms range from 1-10 mm while those made by roots are from 0.1-2 mm (Dexter, 1986). In early experiments, Wiersum (1957) found that roots could only penetrate pores with larger diameters than the root tips, but Scholefield and Hall (1985) found that the roots of perennial ryegrass (*Lolium perenne* L.) were able to penetrate much smaller pores. A study on the penetration of biopores by wheat roots determined that pores 0.2-0.5 mm had no effect on root growth, while pores 0.5-1.0 mm increased root growth (Volkmar, 1996).

The presence of biopores in the soil has been shown to affect crop root growth both in simulations (Jakobsen and Dexter, 1988) and under field conditions (Edwards and Lofty, 1978; Wang et al., 1986; Stone et al., 1987). Large biopores may not be beneficial for root growth due to poor root-soil contact for the transfer of water and nutrients, and may cause roots to signal the plant to slow growth under unfavourable conditions (Passioura and Stirzaker, 1993). Stirzaker et al. (1996) found that a network of small pores was more favourable for barley and pea (*Pisum sativum* L.) root growth than the presence of large biopores. Volkmar (1996) did not find that biopores from 0.2-1.0 mm had any effect on the nitrogen uptake of wheat roots.

Plant species differ in their ability to penetrate compacted soil and form biopores. Materechera et al. (1991) evaluated the ability of 22 plant species to penetrate strong soil. The roots of all species displayed reduced root elongation and increased diameters in response to high soil strength. There were differences among all species, but in general dicot species, having larger root diameters, were better able to penetrate strong soils than monocot species. The difference among crop species allows management strategies for natural alleviation of compaction to select superior species. A study of corn and soybean cultivars showed that genetic variation for the ability to penetrate strong soils also exists within a species (Bushamuka and Zobel, 1998).

Perennial forage crops, because of their extensive root biomass and continuity of their root systems over several years, have great potential to create a network of biopores and perform biological tillage. In a study using minirhizotrons to observe the root growth of corn and alfalfa (*Medicago sativa* L.), Rasse and Smucker (1998) found that the proportion of roots recolonizing biopores from the previous crop were 18% for corn after corn, and 41% for corn after alfalfa.

2.3 Forages and Soil Structure

Soil structure is important for plant growth in providing a framework for anchorage and access to water, oxygen, and nutrients. There is no single soil characteristic that can indicate good soil structure, but rather optimum soil physical properties will vary with soil type, crop and climate (Kay, 1990). According to Letey (1985), the four soil factors that directly affect root growth and crop production are soil water, aeration, temperature and mechanical resistance. Other physical properties, such as bulk density, texture, aggregation, infiltration, etc. will impact on crop production by the way they influence these four direct factors.

One of the benefits of incorporating forage crops in rotation is the improvement of soil structure. The influence of forage crops on soil physical properties is related to the formation of a biopore network, and to increases in soil organic matter additions by these crops. Properties such as porosity, saturated hydraulic conductivity and infiltration are greatly influenced by the size and connectivity of pore structure, whereas aggregation and aggregate stability are generally correlated with organic matter levels (Stone and Buttery, 1989; Haynes et al., 1991; Francis et al., 1999; Rasse et al., 2000).

There have been many previous studies on the changes of soil physical properties by forage crops. Forages have been found to affect the soil pore system through increasing total porosity, macroporosity, infiltration, or saturated hydraulic conductivity (McKeague et al., 1987; Meek et al., 1990; Rasse et al., 2000). They have reduced penetration resistance and alleviated soil compaction (Radcliffe et al., 1986; Alakukku, 1998). Soil aggregation or wet aggregate stability has also been found to increase under forage crops (Haynes et al., 1991; Francis et al., 1999; Bissonnette et al., 2001).

With regards to using periods of pasture to improve soil structure conditions within a mixed cropping system, it is important to determine the length of forage stand needed to ameliorate the soil. In New Zealand, Francis et al. (2001) found that the improvements to soil structure under 3 yr of pasture was equivalent to the decline after 3 yr of annual cropping and recommended that equal lengths for each phase were needed to maintain soil structure. In another study, McQueen and Shepherd (2002) found that most soil degradation occurred within the first 4 yr of annual cropping. In the Argentine mixed cropping systems, the optimum length of each rotation phase was found to be a maximum of 7 yr for annual cropping and a minimum of 3 yr for pasture (Studdert et al., 1997).

2.4 Agriculture and Climate Change

Global concern about climate change has increased in recent years as human activities are starting to have noticeable effects on our environment. The global average surface temperature has increased 0.6°C during the last century and is predicted to increase an additional 1.4-5.8°C over the next 100 years (Intergovernmental Panel on Climate Change (IPCC), 2001). As well as an increase in temperature, changes include a decrease in snow and ice cover, and an increase in sea level. These changes are being attributed to an increase in the concentration of greenhouse gases in the atmosphere.

Agriculture contributes over 20% of anthropogenic greenhouse gas emissions, mainly from the release of methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2001). Climate change will have a direct impact on agriculture as increased temperature and carbon dioxide (CO_2) levels will affect plant physiology, altered precipitation patterns will affect crop production, and increased sea levels will reduce land area. Climate change may also influence agriculture practices indirectly as efforts are made to reduce emissions from the agriculture sector. There is much interest in the other effect that climate change may have on agriculture, by creating an opportunity to mitigate the release of CO_2 and sequester carbon.

Agricultural soils can act both as a source and a sink for carbon through the addition and decomposition of organic matter. Estimates from the IPCC (IPCC, 2001) state that agricultural soils could sequester 23 to 44 Pg C by 2050. While this may represent only 3-6% of total global carbon emissions, increasing soil organic matter may be one of the least expensive mitigation options and would allow time to develop more extensive strategies (Paustian et al., 1997a; IPCC, 2001).

Policy makers are exploring the prospects of designing a carbon credit trading system in which companies would receive credits based on emission or sequestration activities. One example of this credit trade involves a group of Canadian energy companies that have made an agreement with US farmers to pay CAN$1.50-13.00 ha^{-1} yr^{-1} to convert to no-till farming in exchange for claiming credits for the carbon stored in their soils (IPCC, 2001). Therefore, the possibility exists that a new carbon market may emerge and farmers may receive economic benefits to adopt management practices that enhance carbon sequestration. There is new research going on in Uruguay in hopes that carbon credit trading can become a new source of income for Uruguayan farmers, if such policies are put into place.

2.5 Management Practices for Carbon Sequestration

The organic matter content and rate of change of organic matter for a given soil are determined by climate, vegetation, soil type, and management factors. Soil organic matter increases under management practices that increase carbon inputs to the soil and/or decrease the rate of soil organic matter decomposition. This results in a net carbon balance favourable for sequestering carbon. Sequestered carbon has been defined as stored carbon that is physically or chemically protected from decomposition (Carter and Gregorich, 1996).

Management practices that increase organic matter will vary with region, depending on environmental and socioeconomic factors (Paustian et al., 1997a), but include intensifying cropping systems, decreasing tillage, increasing use of perennial vegetation, and increasing use of fertilizer or manure (Janzen et al., 1998; Dalal and Chan, 2001). Increasing cropping system intensity involves decreasing fallow and adopting more diverse crop rotations. This includes incorporating perennial grasses or legumes in a crop rotation. In a simulation of carbon sequestration in Europe, it was estimated that the conversion of all arable land to a pasture-annual crop rotation could store 3.9 Pg C over 100 years (Smith, 1999). If carbon storage in agricultural soils is accepted in a carbon credit trading system, then calculation of a net carbon balance will have to account for greenhouse gas emissions from the entire production system, for example, including fossil fuel emissions from field operations or losses of N_2O from fertilizers and/or legumes (Janzen et al., 1998; Smith, 1999).

It is important to note that the capacity of soils to store carbon is finite (Paustian et al., 1997a; Janzen et al., 1998). Agricultural soils are able to increase soil carbon levels because their soil organic matter has been depleted over years of cultivation from native sod (Paustian et al., 1997a), and the amount of carbon that can be added will be limited by the reach of a new equilibrium or steady state. The initial organic matter content for an individual soil may restrict its potential to sequester carbon (Janzen et al., 1998). A soil that has been severely depleted of its native organic matter will have greater potential to sequester carbon than a soil that has received fewer losses.

2.6 Measuring Carbon Sequestration

Since the recognition of soils as a sink for carbon, there has been much research on soil organic matter dynamics and techniques to measure changes in soil carbon. Several researchers have constructed various models to simulate soil organic matter dynamics (van Veen and Paul, 1981). These models generally partition organic matter into several theoretical pools, which differ in age and rate of turnover (Parton et al., 1987). The model by Parton et al. (1987) defined three organic matter pools as active, slow, and passive with turnover rates of 1-5, 20-40, and 200-1500 yr, respectively. These models need to be verified with organic matter behaviour *in situ*. Various organic matter fractionation procedures have been developed in attempts to isolate and verify the pools in these models (Carter and Gregorich, 1996; Christensen, 2001).

There are many different approaches to measuring soil organic carbon including chemical fractionation, physical fractionation, use of tracers or carbon isotopes, microbial biomass measures and carbon mineralization potentials (Carter and Gregorich, 1996; Collins et al., 1997). Physical fractions of soil organic matter are thought to be more closely related to simulation pools, because they reflect the influence of the physical location of organic matter on its susceptibility to decomposition (Elliot and Cambardella, 1991; Christensen, 2001). More recent developments with ^{13}C-nuclear magnetic resonance spectroscopy (NMR), solid-state cross-polarization with magnetic angle spinning (CP/MAS-NMR), and pyrolysis-soft field ionization mass spectrometry (Py-FIMS) technologies have allowed for chemical analysis on physical fractions of soil organic matter and provided additional information on the nature and composition of the isolated fractions (Collins et al., 1997).

2.6.1 *Physical Fractionation*

An extensive review of physical fractionation techniques is given by Christensen (2001). Physical fractionation of soil organic matter developed out of recognition that organic matter dynamics are regulated by soil structure. The physical location and protection of organic matter is important in determining its stability, since physical isolation can protect organic compounds from the actions of decomposers and their enzymes (Ladd et al., 1993). Several researchers have found evidence to support a conceptual theory of aggregate turnover that relates the biological process of organic matter decomposition to the formation and breakdown of soil aggregates (Golchin et al., 1994; Six et al., 1998; Six et al., 2000; Gale et al., 2000).

This concept of aggregate hierarchy describes the decomposition of plant residues into smaller and more resistant carbon compounds, and their incorporation into aggregates and organomineral complexes, where they are protected from rapid decomposition. Recently added soil organic matter forms close associations with soil particles and is bound into large, stable aggregates. As this organic matter is broken down and decomposed, the aggregates become unstable and separate into free degraded organic material, smaller microaggregates, and carbon enriched organominerals. These particles will reform into macroaggregates around a nucleus of new organic material as the process of aggregate formation and degradation is dynamic and ongoing.

Physical fractionation procedures may be based on size or density separations, or a combination of both (Christensen, 2001). These fractions are usually defined as free, particulate, or mineral associated organic carbon. The light, or free, fraction is from organic matter that is loose in the soil and not attached to any particles. The particulate fractions can be further separated by size or location and are located within or between aggregates where they bind particles together and stabilize aggregates. Mineral associated organic carbon is composed of resistant organic compounds that are closely associated with clay, silt, and sand particles.

The proportion of particulate organic matter in a soil is affected by land use, vegetation and environmental factors such as climate, soil type and microbial population (Christensen, 2001). Free and particulate organic matter can compose 15-40% of the organic matter in the surface of soils under permanent vegetation and less than 10% under cultivation (Christensen, 2001). The particulate organic matter fraction is believed to undergo the most changes under tillage. Tillage disrupts soil aggregates and leaves particulate organic matter exposed to rapid decomposition. Tillage has been observed to decrease soil aggregation and the particulate organic matter fraction (Cambardella and Elliot, 1992; Quiroga et al., 1996; Six et al., 1998).

Researchers have studied the turnover times for various carbon physical fractions. Monreal et al. (1997) determined turnover times for three organic carbon fractions in the 0-15 cm layer of a cultivated soil. Organic carbon found in aggregates >250 μm had a turnover of 14 yr, the fraction in aggregates 20-250 μm had a turnover of 61 yr and the <50 μm microaggregate fraction had a turnover of 275 yr. Carbon turnover rates found by Buyanovsky et al. (1994) were 0.5-3 yr for vegetative fragments, 2-10 yr for aggregates and >400 yr for mineral particles. They distinguished several carbon pools from their turnover times as described in various models but emphasized that organic carbon dynamics in soil involves transition and overlap from one pool to the next.

The free and particulate organic matter fractions are the youngest fractions and have a rapid turnover. Therefore, they are more sensitive to changes in organic matter additions and may be used as early indicators to detect the effect of a change in management practice on soil organic matter levels (Quiroga et al., 1996; Chan, 1997; Janzen et al., 1998). Because the large, stable pool of soil organic carbon that is associated with mineral particles changes very slowly, the effects of change in management may only be noticed after many years. Long-term experiments can be valuable for evaluating the implications of management practices on soil organic carbon (Paustian et al., 1997b).

2.7 Forages and Carbon Sequestration

Increasing the use of perennial crops is one of the management strategies proposed for carbon sequestration. In a review of strategies to increase soil carbon levels, Paustian et al. (1997a) cited that crop rotations in Europe including 3 yr or more of forage had 35% more soil carbon than those without. Including forages in crop rotations can increase soil organic matter through several mechanisms, such as increasing carbon inputs below-ground, increasing formation of stable aggregates, which protect organic matter, decreasing the amount of tillage, and decreasing soil erosion (Paustian et al., 1997a).

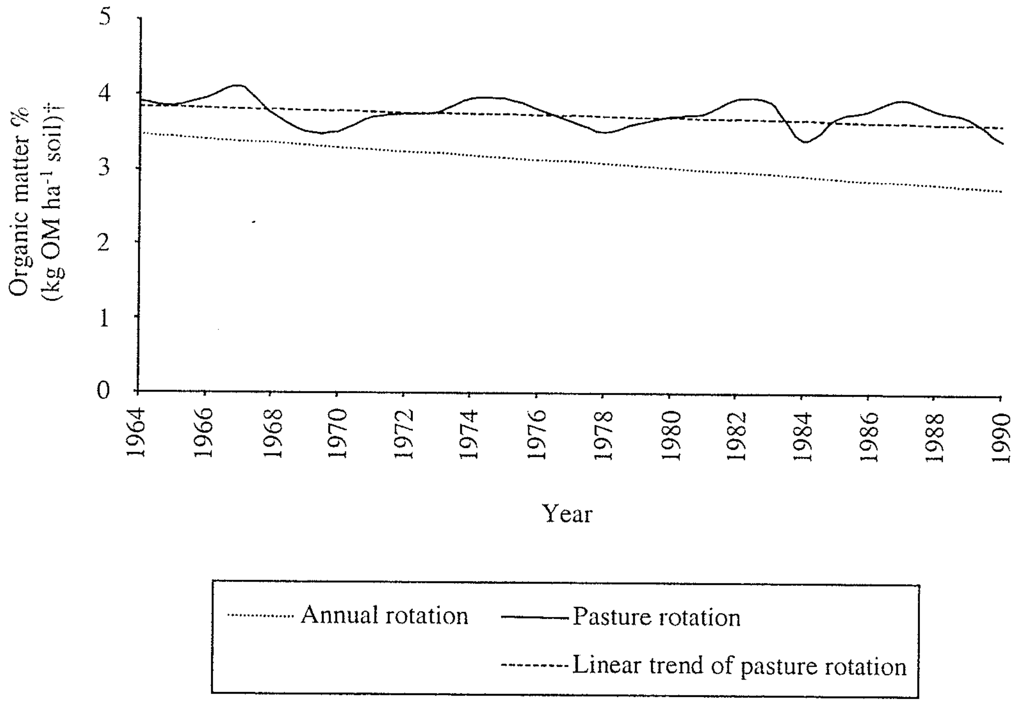
In a long-term rotation study at Breton, Alberta the organic matter in a 5 yr rotation including two years of forage was 20% higher than in a wheat-fallow rotation (Juma et al., 1997). Rotation studies in Saskatchewan found that the inclusion of a green manure or hay in a wheat rotation increased organic matter at Indian Head, but not at Melfort (Campbell et al., 1997). The absence of a rotation effect at Melfort was attributed to the high level of organic matter already present in the soil.

In an Australian study, Chan (1997) examined changes in total and particulate organic carbon when annual wheat cropping was converted to pasture and vice versa. The particulate organic carbon fraction was the form that was preferentially lost under annual cropping, or gained under pasture. The change in this fraction represented 70% of the difference in total organic carbon between pasture and annual cropping.

In another experiment, Chan et al. (2001), compared the changes in soil organic carbon of different forage species. After 4 years, total organic carbon was highest under alfalfa and lowest under fallow, with barrel medic (*Medicago trunculata* Gaertner) and consol lovegrass (*Eragrostis curvula* (Schrader) Nees) levels intermediate. The labile carbon fractions accounted for 78-92% of the increases in organic carbon from the pasture species, indicating that youngest carbon fractions were responsible for most of the change in soil organic carbon after 4 years of forages. The authors also noted that the gain in organic carbon observed after 4 years of alfalfa was only 15% of the total loss in organic carbon that was observed at the site after 50 years of cultivation.

2.7.1 *Forages and Organic Matter in Uruguay*

At the INIA La Estanzuela research station in southwestern Uruguay, a long-term rotation experiment was established in 1963 to compare cropping systems that differed in the time spent under periods of pasture or arable cropping. Díaz (1992) reported the changes observed in the organic matter levels of the 0-20 cm depth in this experiment from 1964-1990 as determined by annual measurements. Organic matter was observed to decrease over this time period in all rotation treatments. The organic matter levels of two of the treatments, a rotation of annual crops and a rotation of a 3-4 yr grass-legume pasture with 3-4 yr annual crops, are shown in Figure 2.1. The annual rotation showed a constant, linear decrease in organic matter over the 26 years. Organic matter levels in the pasture rotation fluctuated with increases during periods under pasture and decreases during periods under annual cropping. However, the losses during the arable periods exceeded the gains under pasture, and organic matter levels decreased with time in the pasture rotation. The average annual losses in soil organic matter were 0.0268% for the annual rotation and 0.0083% for pasture rotation. The inclusion of pasture in the crop rotation slowed the rate of surface soil organic matter decline. The average annual loss of organic matter during the arable phase of the pasture rotation was found to be 0.1624%. This rate of loss is greater than in the annual rotation, and is contributed to the organic matter added during the pasture phase being highly labile and easily decomposed.



†Organic matter % was converted to an area basis based on a bulk density of 1.25 g cm^{-3}.

Figure 2.1. Organic matter content at 0-20 cm for the annual and pasture rotations of the long-term rotation experiment at La Estanzuela during 1964-1990. Adapted from Díaz (1992).

The loss of organic matter due the cultivation, or change in management practice, has been shown to follow as asymptotic decline as a new equilibrium is reached in the long-term. Because the declines in soil organic matter were constant and linear over a 26 yr period in the long-term rotation experiment at La Estanzuela and did not show this characteristic decline in the rate of change with the approach of a new steady state, erosion processes were assumed to be large factor in the observed losses. This could not be directly confirmed, since erosion measurements have not been performed on the experiment. Using the Universal Soil Loss Equation, García (1992) estimated the soil erosion losses to be 23.72 and 9.39 t ha^{-1} yr^{-1} for the annual and pasture rotations, respectively. The pasture rotation will likely have lost less organic matter due to its lower rate of soil erosion. Hao et al. (2001) found that a corn-wheat-meadow-meadow rotation lost 15 times less soil organic carbon due to erosion than continuous corn in an Ohio watershed.

2.8 Erosion and Carbon Sequestration

The influence of soil erosion on organic matter dynamics, and its impact on carbon sequestration is not well understood. Soil erosion removes the surface soil layer, which is the part of the soil profile that generally contains the highest concentration of organic matter. As well, eroded sediments are enriched in soil organic carbon, as compared to the soil they were removed from (Hao et al., 2001; Jacinthe et al., 2002), indicating that organic carbon is preferentially removed during erosion processes.

Research is needed to determine whether the loss of soil organic matter due to erosion processes results in a loss of stored carbon, in order to properly account for the effect of soil erosion on carbon sequestration (Paustian et al., 1997a). A recent study by

Jacinthe et al. (2002), examined the carbon mineralization and release of CO_2 from eroded sediments. They simulated erosion losses from rainfall in three tillage treatments consisting of no-till, chisel till, and moldboard plow. They found that 28-46% of the organic carbon in eroded sediments was mineralized after 100 days. The no-till treatment had the lowest amount of eroded sediment, but the highest mineralization rate and potentially mineralizable carbon content, which resulted in the highest cumulative CO_2 production. This was attributed to the carbon in the no-till sediment being more labile and more rapidly mineralized. The authors note that this study shows that soil erosion can have a large influence on carbon dynamics, even in systems designed to decrease erosion rates.

2.9 Soil Depth and Carbon Sequestration

Studies of organic carbon rarely look at changes in carbon below 30 cm, because most of the carbon inputs to the soil are made in the top of the soil profile. However, a study by Gill et al. (1999) examined the hypothesis that the decomposition rate of soil organic matter varies with depth, since observed root biomass and soil organic matter distributions were not the same throughout a soil profile. They used ^{14}C labeling to measure the distribution of one year's growth of a shortgrass steppe (*Bouteloua gracilis* (H.B.K.) Lag., *Opuntia polyacantha* Haw., *Sphaeralcea coccinea* (Pursh) Rybd., and *Artemisia frigida* Willd.) and calculated decomposition rates up to 100 cm. The estimated decomposition rates showed that the most rapid decomposition occurred at the intermediate depths (10-35 cm), with decomposition being slower at the soil surface and deeper in the profile. They concluded that decomposition rates changed with soil conditions throughout the profile and suggested that water availability was likely the most influential factor affecting decomposition, at least in the upper profile. They recovered 17.5% of the labeled carbon below 50 cm, which indicated that carbon dynamics in the deep soil profile are influenced by the current vegetation.

2.10 Root Systems

Crop roots are obscured from view by the soil matrix and are rarely considered or investigated in physiology or agronomy studies. However, roots serve important roles in plant anchorage, and uptake of water and nutrients (Fitter, 1996). As well, they can have a part in storage, propagation, dispersal, and the synthesis of plant growth regulators. As mentioned previously, roots can also function to ameliorate the soil or sequester carbon. The root growth of a plant is influenced by its genetics and the surrounding environment and can vary within a species as well as between species, and this makes attempts to classify root systems difficult (Lamba et al., 1949; Fitter, 1996).

Root systems can be generally classified according to plant type, monocot or dicot, as these systems have some distinct differences. Klepper (1992) reviews the development and growth of monocot and dicot root systems. A general description of each root system follows. Monocot root systems referred to as fibrous root systems as they have many fine, highly branching root axes. Monocot roots do not experience secondary growth and will maintain a small root diameter. Seminal roots will tend to grow in a downward direction, and crown roots will initially grow at an angle before turning downwards in the soil. The higher order, branch roots will tend to decrease in length and diameter. Dicot root systems can have various forms with one of the more common being a taproot system, or some modification of a taproot. This taproot originates from the primary root and vertically downwards in the soil. Dicot roots do undergo secondary growth, which can increase the diameter of the taproot. Lateral root branches will form off the taproot and tend to grow out horizontally before turning downwards. They will often have a much smaller diameter than the taproot. These are general characteristics of two types of root systems, but root growth will be altered by soil conditions such as water content, nutrient status, strength, and aeration (Weaver, 1926).

2.10.1 *Measuring Roots*

Crop roots often receive little study because the techniques for observing and measuring them can be time-consuming and yield inaccurate results. Many methods also require destructive sampling and repeated measures on a single plant are not possible. Böhm (1979) has provided an extensive review of the various methods of root system study with a discussion of the benefits and drawbacks of each method. Methods for field observations of roots include destructive sampling methods such as excavation, monoliths, profile wall, or core-break. Nondestructive root measurements include rhizotrons, or indirect measures through the use of soil water content, or radioactive tracers. The ease of separating roots from the soil has been advanced by the development of various root washing devices (Cahoon and Morton, 1961; Smucker et al., 1982) and imaging technology has facilitated length measurements of washed roots (Costa et al., 2000).

The core-break method has received greater use due to its potential to be a very rapid method of root assessment (Böhm, 1979; Bennie et al., 1987). With this technique, cores are removed from the soil, broken in half, and the visible root axes on each cross sectional surface area are counted and averaged. The count of root axes is linearly related to root length density values, though calibrations would be required for each crop species, soil type, and management practice (Drew and Saker, 1980; Bennie et al., 1987; Bland, 1989).

The choice of which root observation method to use depends on the aim of the study, because each will measure different root parameters (Böhm, 1979; Köpke, 1981). Root parameters that can be measured include root number, length, weight, and diameter. Selected root parameters are associated with different study objectives concerning the role and function of roots (Böhm, 1979). Root number is used to make inferences about root length, which is the parameter most often used to assess water and nutrient uptake. Root weight is valuable for assessing plant resource allocation to roots and root additions to soil organic matter. Root diameter can be used in studies of biopores or soil penetration.

Recent developments in root studies have led to the use of minirhizotrons to evaluate root growth. These are see-through tubes that are installed in the soil and permit observations of roots over time, now with the aid of video recording equipment (Upchurch and Ritchie, 1983). Minirhizotrons have an advantage as a nondestructive root study technique and can permit the observation of root growth over time. Minirhizotrons can be used to calculate root length density (Merrill and Upchurch, 1994), and may be valuable in measuring root turnover (Cheng et al., 1991). Rasse and Smucker (1998) used minirhizotrons to observe root recolonization of biopores. Future work on observing and measuring root dynamics will likely be aided by this method of study.

2.11 Crop Descriptions

2.11.1 *Tall Fescue*

Tall fescue is a deep rooted perennial bunchgrass commonly used for forage in Uruguay. It is often found in grass-legume pasture mixtures with birdsfoot trefoil or clover species. It has a fibrous root system typical of grass species, though literature on tall fescue root systems is limited. In a study of root distributions of several grass species, Sheffer et al. (1987) found that 50% of the root weight distribution of tall fescue was located in the top 12 cm of the soil profile. Bennett and Doss (1960) found that tall fescue root distributions vary with soil moisture conditions, as the proportion of root mass in the surface 15 cm was 54% under high moisture levels and 37% under low moisture. Decreasing soil moisture increased rooting depth. Another study of fescue roots, Torbert el al. (1990), examined their ability to penetrate a compacted layer. In this experiment fescue cultivars with root diameters from 0.92-1.03 μm were able to penetrate the compacted layer and extract soil water lower in the profile, whereas cultivars with smaller diameters of 0.16-0.19 μm were restricted to the soil above the compacted layer.

2.11.2 *Alfalfa*

Alfalfa is one of the oldest plants grown solely for forage and is currently distributed all over the world (Michaud et al., 1988). Alfalfa is a legume and benefits from a symbiotic relationship with *Rhizobium* that fix nitrogen. The prevalence of alfalfa in Uruguay is not as great as in neighbouring Argentina, but it is used as a pasture and hay in some areas (Michaud et al., 1988).

Alfalfa is a deep rooted perennial with a prominent taproot that grows vertically downward and gives rise to several lateral roots. Previous studies have shown that alfalfa roots may penetrate beyond 1 m (Lamba et al., 1949; Upchurch and Lovvorn, 1951) and even 3 m by the end of the second growing season (Weaver, 1926). Research on the alfalfa root distribution has shown that typically over 50% of the root weight distribution is located in the top 20 cm of the soil profile (Lamba et al., 1949; Bennett and Doss, 1960). This is due to the large taproot present at the soil surface. Upchurch and Lovvorn (1951) reported taproot diameters at the soil surface to range from 2.74 mm in a 7 month stand to 13.51 mm in a 6 yr stand.

Lateral roots tend to be absent from the surface and originate lower in the profile, but this will vary with environmental conditions. Weaver (1926) found that the rooting pattern of alfalfa changed under different soil moisture conditions. Under dry conditions plants were more shallow rooted with numerous, long branches as compared to well-watered plants that maintained a dominant taproot, few laterals, and penetrated deeper in the soil. Bennett and Doss (1960) found alfalfa root penetration to be greater under low than high soil moisture conditions. Soil structure may also influence root distribution, as Carlson (1925) found that alfalfa produced a large taproot with few branches in a sandy soil, whereas in a compact clay loam soil it had a greater number of lateral roots. Conversely, Upchurch and Lovvorn (1951) reported more lateral roots in sandy soil than clay soil. Nutrient availability is another environmental parameter that can influence alfalfa root distribution, as a lack of phosphorus was found to restrict roots to the top 20 cm of the soil, whereas under fertilization roots were more evenly distributed up to 40-50 cm (Sanderson and Jones, 1993).

2.11.3 *Chicory*

Chicory (*Cichorium intybus* L.) is a perennial plant that is perhaps more well known as a human food source, as a salad green or coffee substitute, but also is grown in pastures for livestock and is found in Uruguay (Mitch, 1993). Chicory has a prominent taproot and its vegetation is characterized by a basal rosette, which grows erect up to 30-90 cm after vernalization (Mitch, 1993; Li et al., 1998). There is little information in the literature on the root growth and distribution of forage chicory. Recent studies on chicory have focused on its adaptation in northeastern US pastures, because of its drought tolerance and high summer production (Sanderson and Elwinger, 2000), and its potential for a cover crop to control nitrogen leaching in Sweden (Zagal et al., 2001). An experiment on the seedling development of chicory, which measured root growth 74 days after planting, showed that chicory had a dominant taproot of 4.7-5.5 mm diameter with many lateral roots (Sanderson and Elwinger, 2000).

2.11.4 *Sorghum*

Grain sorghum is grown in Uruguay as a summer annual crop with the crop yield being used as animal feed. The growth stages of sorghum have been described by Vanderlip and Reeves (1972) using a numerical scale from 0 to 9. The time for a given sorghum plant to reach each stage of development will depend on the genetics of the plant and the environmental growing conditions. Some key stages in the development of sorghum and accumulation of dry matter are described in Table 2.1.

Grain sorghum is considered to be a relatively drought resistant crop. It has a fibrous root system similar to that of corn, but has been found to have more secondary roots per unit length of primary root than corn (Weaver, 1926). This well developed root

Table 2.1. Description of the growth and development of sorghum. Growth stages are according to Vanderlip and Reeves (1972) and growth descriptions are adapted from Kansas State University (1998), and Kramer and Ross (1970).

Growth Stage	Description
3 – Growing point differentiation	– growing point changes from producing leaves to producing the panicle – 10-15% of nutrient uptake has occurred – cumulative water use† 100-125 mm – approximate height 20-30 cm
6 – Half bloom	– half of the plants are flowering – cumulative water use 300-350 mm – 70-85% of nutrient uptake has occurred
9 – Physiological maturity	– grain is no longer increasing in dry weight – cumulative water use 550-600 mm

† Indicates cumulative water use when water is not limiting.

system contributes to its better drought tolerance. Drought stress has been shown to affect sorghum development by slowing the rate of development and delaying panicle initiation and flowering (Craufurd et al., 1993).

A study done in Kansas on the root distribution of sorghum in a silt loam, found maximum rooting depth to be at approximately 1.8 m (Stone et al., 2001). The sorghum plants had reached 87% of the maximum rooting depth by the half bloom stage. The rate of rooting front development ranged from 0.8-4.5 mm day^{-1}. An earlier study of sorghum roots in a loam soil in Arizona, found that 90% of root activity was contained in the zone extending 90 cm vertically in the profile, and 38 cm laterally from the sorghum plant (Nakayama and van Bavel, 1963). These authors calculated root growth rates of 2-5 cm day^{-1}.

3. ROOT CHARACTERIZATION OF FORAGES

3.1 Abstract

Forage crops are widely grown in the mixed cropping system of southwestern Uruguay. There is renewed interest in the use of forages for soil improvement and carbon sequestration, but the root growth of forages has received little study. Field observations were made of the root systems of tall fescue, alfalfa and chicory. Soil core samples were used to measure root count and biomass distributions to a depth of 1 m. Roots were detected to a depth of 1 m for all species, though at least half of the root biomass for each species was located within the surface 30 cm of the profile. The distribution of root counts differed with the greatest number of root axes found above 20 cm for tall fescue and chicory, and below 20 cm for alfalfa.

3.2 Introduction

Forage crops are a principal component of the mixed cropping system practiced in southwestern Uruguay. Incorporating perennial forages in crop rotations provides many benefits such as erosion protection, breaks from weed pressures, increased soil organic matter (Entz et al., 2002), and biological tillage of soil in no-till systems (Dexter, 1991). There is renewed interest in forage crops because of their potential for soil improvement and carbon sequestration. Perennial forage crops have the capacity to develop more extensive root systems than annual crops, because of the growth and continuity of their root systems over several years (Weaver, 1926). These roots may be influential in performing biological tillage or adding carbon, especially deep in the soil profile.

Roots are often the parts of a plant that receive little study because it is time-consuming and difficult to accurately sample for and measure root systems under field conditions. The core-break method has been found to be a rapid method for evaluating root distributions in the field (Böhm, 1979; Bennie et al., 1987). Root counts obtained with the core-break method are linearly related to the root length density of a sample (Bland, 1989). To convert root counts to root length density values, calibration equations should be established for each crop species, soil type, and management practice and may change with crop development, or soil depth (Drew and Saker, 1980; Bennie et al., 1987; Bland, 1989). However, counts of root axes from the core-break method are sufficient to indicate relative root growth and distribution (Köpke, 1981). The design of root washing devices has facilitated the separation of roots from soil and measurement of root biomass (Cahoon and Morton, 1961; Böhm, 1979).

Root growth and distribution is genetically and environmentally controlled. The pattern of root distribution within a soil profile differs between crop species and locations as soil type, moisture, fertility, and other environmental variables change (Weaver, 1926; Lamba et al., 1949). The rooting characteristics of forage crops have not been examined in Uruguay and this study was conducted to observe the root distributions of tall fescue, alfalfa, and chicory under field conditions.

3.3 Materials and Methods

The forage species selected for root characterization were tall fescue, alfalfa, and chicory. The stand of each species was located on a silty clay loam soil at the INIA La Estanzuela research station in southwestern Uruguay. Mean monthly precipitation and temperature for this region are listed in Appendix A. The management practices for each forage stand are listed in Table 3.1. The forage stands were in the third, second and eleventh years, respectively, for the tall fescue, alfalfa and chicory.

Table 3.1 Description of the management practices for three forage stands.

Species	Cultivar	Seeding Date	Seeding Rate	Management
Tall fescue	Estanzuela Tacuabé	May 1999	10 kg ha^{-1}	harvested for seed, never grazed
Alfalfa	Estanzuela Chaná	Aug. 2000	12 kg ha^{-1}	grazed by cattle
Chicory	unknown	1990	unknown	left to naturally reseed, mowed

Root samples for all species were removed from the field during November 2001. Eight core samples per forage species were removed from random, weed-free locations within each stand. A hydraulic soil corer was used to extract a 4.25 cm diameter soil core to a depth of 100 cm. Each core was cut into 10 cm depth increments and transferred to the lab.

Root axis distribution was determined using the core break method (Böhm, 1979; Bennie et al., 1987). Each 10 cm core segment was broken in half and the visible root axes on each surface area were counted with the aid of a magnifying glass. The same individual processed all of the samples. After counting the number of root axes, the roots were separated from the soil with a root washer (Delta-T Devices, Cambridge). All collected roots were dried to a constant weight in an oven at 60°C to determine the root biomass in each core segment.

Measurements for each 10 cm depth increment were averaged across all eight core samples for each forage species. A value of the root biomass of individual roots was calculated by dividing the root biomass by number of root axes in each depth increment for each forage species.

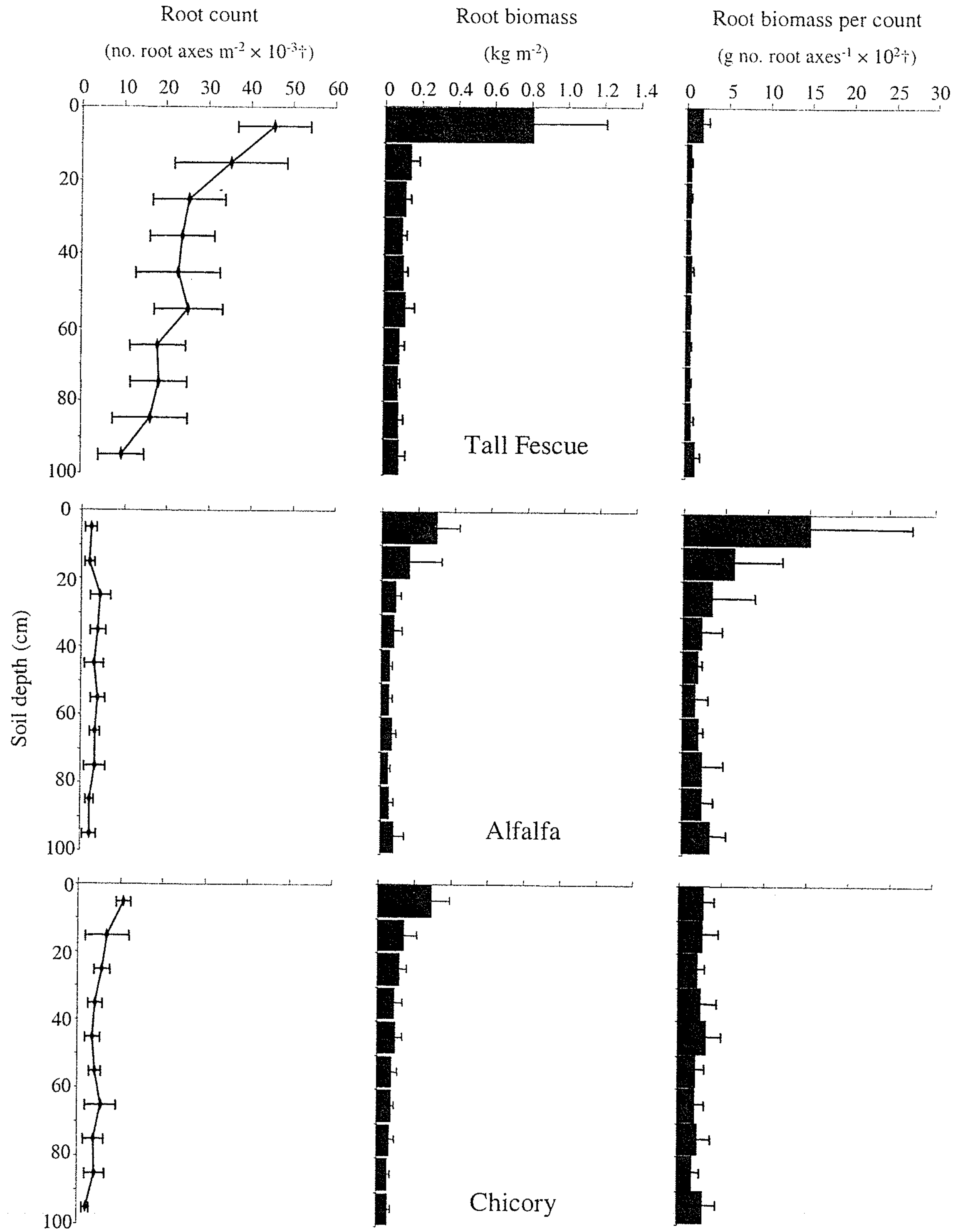
3.4 Results and Discussion

This study was not designed for a direct comparison between the forage species, but rather for observational information on the root growth of each species. The distributions of root counts and root biomass for each species are presented in Fig. 3.1. All species had roots present in the 90 to 100 cm depth, indicating that forage roots are able to penetrate beyond 1 m in the soils studied. Alfalfa roots have been observed to penetrate beyond 1 m (Lamba et al., 1949; Upchurch and Lovvorn, 1951) and even to depths of 3 m by the end of the second growing season (Weaver, 1926).

The number of tall fescue root axes decreased with soil depth. Almost half of the 1.7 kg m^{-2} total tall fescue root biomass was located in the top 10 cm of the profile. The high biomass value and large standard error for the 0 to 10 cm depth may have been due to the large amount of organic matter present in the samples at this depth. This material was difficult to separate from the tall fescue samples during the root washing procedure. A study of tall fescue root distribution in a silt loam soil in Missouri found that 50% of the root biomass in a 84 cm soil profile was located in the top 12 cm (Sheffer et al., 1987). Other grass species have exhibited root biomass proportions of 44 to 87% in the upper 15 cm depth for two to four year old stands (Pavlychenko, 1942).

Grass species have fibrous root systems, which produce many branching roots with small diameters. The low values for the root biomass per count imply that tall fescue had very fine roots. The consistent values below 10 cm indicate that the diameter of fescue roots was relatively constant across soil depths.

In the alfalfa root system, root counts were slightly higher between the 25 to 55 cm depths than the surface soil, indicating greater root branching at these depths.



† Reported values equal actual values times the indicated factor.

Figure 3.1. Root count, root biomass, and root biomass per count distributions of three forage stands to a depth of 1 m. Values are means of eight replicates with horizontal bars representing the standard errors of the means.

Approximately half of the total 0.9 kg m^{-2} root biomass was located in the top 20 cm of the soil profile. Lamba et al. (1949) observed that 57% of the root biomass for a two year old alfalfa stand was located in the upper 20 cm of a 120 cm root profile. Large root biomass in the surface soil and root branching further down in the profile, support previous studies of alfalfa root systems, which found alfalfa has a deeply penetrating taproot, relatively few lateral roots within the surface soil layers, and short laterals further down in the profile (Weaver, 1926; Upchurch and Lovvorn, 1951).

The two upper depths had the highest values for root biomass per root count in the alfalfa root profile at 15.0 and 6.1 g no. root $axes^{-1} \times 10^{-2}$, respectively. Root thickness would be greatest at these depths. These values further support the presence of a taproot system. Taproot diameter and length depend on the age of the alfalfa stand (Upchurch and Lovvorn, 1951). The large standard errors for root biomass at the 0 to 20 cm depths were due to the large variation between samples that contained part of a taproot and those that did not.

Chicory, like alfalfa, exhibits a taproot system. However, unlike alfalfa, 35% of the chicory root counts were present at the 5 to 15 cm depth. This implies that there was root branching within the upper soil profile. Total chicory root biomass was 1.1 kg m^{-2}. Root biomass decreased with depth and half of the chicory root biomass was located in the upper 30 cm of the profile. The root biomass per root count varied from 3.2 to 1.8 g no. root $axes^{-1} \times 10^{-2}$ and was fairly constant throughout the profile, indicating that root thickness varied little with depth. On an observational note, one of the root samples from the 90 to 100 cm depth contained a large, thick root that was more comparable to the roots found in the upper depths. This accounts for the value of 2.9 g no. root axes^{-1} × 10^{-2} for the root biomass per root count at this depth.

The large standard errors for some of the species and depths indicate the spatial variability that is present within the field. Increasing the number of samples, or increasing the diameter of the cores could reduce the variation between samples. In studies using the core-break method in annual crops, samples are taken in-row and between-row to account for the variation in horizontal root distribution (Bennie et al., 1987). Since rows were no longer visible within the forage stands, samples were removed from random locations within each stand.

The core-break method is a rapid method for assessing relative root distribution within the soil profile. The relationship between the number of root axes observed on a horizontal plane and root length density may change with soil depth, if the orientation of roots vary with depth (Drew and Saker, 1980; Bland, 1989). For example, if roots of a forage species become more vertically oriented with rooting depth, the counts of root axes will overestimate the relative root distributions. Observations have been made of alfalfa with lateral roots in the surface soil layers that run horizontally for some distance before growing downwards in the soil (Weaver, 1926). Lateral roots growing parallel to the soil surface may not be observed by the core-break root counts and contribute to the low root counts for alfalfa in the upper 20 cm.

Root distributions are characterized both in terms of root number or length, and root biomass. The root system attribute of interest depends on the focus of the study (Böhm, 1979). Root length distributions are important in relating root development to crop water and nutrient uptake, whereas root biomass distributions reveal the input of organic matter to the soil profile. The ability of a root system to perform biological tillage will be related to root length and root diameter in establishing a network of pores within the soil.

3.5 Conclusions

The roots of tall fescue, alfalfa and chicory were observed under field growing conditions in a silty clay loam soil in southwestern Uruguay. The maximum rooting depth was greater than 1 m for each of the species. Half the root biomass in the 1 m profile was located in the top 10, 20, and 30 cm for tall fescue, alfalfa, and chicory, respectively. The forages exhibited differences in the distribution of root counts with the core-break method. Tall fescue and chicory had a large number of root axes present in the top 20 cm, whereas alfalfa had a greater number of root axes from 20 to 60 cm. These differences reflect the root type and degree of branching for each of the forages.

4. BIOLOGICAL TILLAGE OF FORAGES

4.1 Abstract

One of the potential benefits of including forage crops in crop rotations includes soil structure improvement. The extensive root systems of forage species may perform biological tillage and enhance the production of following grain crops. A field experiment was conducted to determine the effects of 7 yr stands of alfalfa, tall fescue, and chicory on soil properties and subsequent growth of grain sorghum. Early growth and development of the sorghum crop was enhanced in the alfalfa and chicory treatments, but no treatment effects were seen at harvest. Forage treatments had little effect on soil physical properties. The chicory treatment showed reduced soil strength at 20 cm in the soil profile under wet conditions, and the tall fescue had lower bulk density at 9-14 cm. These results show little evidence to support the theory that forages ameliorate soil structure in Uruguay. Treatment effects in this experiment may have been confounded by weed pressure and abundant precipitation. The role of forage crop in performing biological tillage requires further study.

4.2 Introduction

Cropping systems in Uruguay involve a rotation of annual grain crops with perennial grass-legume pastures used for livestock production. Incorporating perennial forages in crop rotations provides many benefits including rotational yield increases, erosion protection, breaks from weed pressures, increased soil organic matter, and biological nitrogen fixation if legume species are used (Entz et al., 2002). In this type of mixed cropping system, the pasture phase is often needed to ameliorate the soil structure, which degrades under annual grain crop production (Studdert et al., 1997; Francis et al., 1999). The length of each phase of the rotation is determined by profitability, persistence of the forages in pasture, and the need to maintain soil structure. In recent years, the area under pasture in Argentina and, to a lesser extent, in Uruguay has been decreasing in favour of cash crop production under no-till (Studdert et al., 1997; Díaz-Zorita et al., 2002). While no-till cropping practices are promoted for soil conservation benefits, subsoil compaction may be a constraint for crop growth under no-till (Martino, 1998; Ferreras et al., 2000). The importance of forage crops in maintaining and improving soil structure in mixed cropping systems needs to be recognized, if their significance in crop rotations can be valued in comparison to grain crops.

Soil structure is an important factor for crop production due to its influences on ease of tillage, soil aeration, water movement, and root penetration. Soil structure is typically managed through various tillage practices, but is also controlled by natural processes such as wetting and drying cycles, freezing and thawing processes, and the actions of roots or soil fauna. The natural amelioration of soil structure through the actions of plant roots or soil organisms, such as earthworms, is referred to as biological tillage. Plants can accomplish biological tillage through several mechanisms. Roots and associated fungal hyphae bind and stabilize soil aggregates, root exudates compounds bind soil aggregates, and roots form channels, called biopores, that remain in the soil after they decompose (Dexter, 1991). The presence of biopores have been shown to influence the root growth of following crops, especially in poorly structured, or compact soil (Edwards and Lofty, 1978; Wang et al., 1986; Stone et al., 1987).

Perennial forage crops, because of their extensive root biomass and the continuity of their root systems over several years, have great potential to perform biological tillage and create a network of biopores in the soil. Previous research on the changes to soil physical properties under forage crops has shown that forages can decrease bulk density and penetration resistance, and increase total porosity, macroporosity, infiltration, hydraulic conductivity and aggregate stability (McKeague et al., 1987; Meek et al., 1990; Haynes et al., 1991; Francis et al., 1999; Rasse et al., 2000; Bissonnette et al., 2001).

This experiment was designed to examine the biological tillage effects of tall fescue, alfalfa and chicory in Uruguay. The objectives were to determine what changes are made to soil physical properties by the forage roots, and to determine how these changes in turn affect the productivity of a following grain crop.

4.3 Materials and Methods

4.3.1 *Experiment Description*

An experiment was initiated in 1992 to investigate the potential biological tillage of several forage species on a silty clay loam soil at the INIA La Estanzuela research station in southwestern Uruguay. The treatments of interest consisted of stands of tall fescue, alfalfa, chicory, and an annual crop rotation. The annual crop rotation with conventional tillage was included as a measure of the initial condition of the soil. Not all treatments were present in each block, so the experiment had an incomplete block design with plots 6 × 24 m. The annual crop rotation was present in each block and enabled comparison among all treatments (Table 4.1).

The experimental site had been under annual cropping with conventional tillage for four years previous to plot establishment. The forage treatments were established in September 1992 with seeding rates of 12 kg ha^{-1}, 18 kg ha^{-1}, and 5 kg ha^{-1}, respectively for the tall fescue cv. Estanzuela Tacuabé, alfalfa cv. Estanzuela Chaná, and chicory cv.

Table 4.1. The physical layout of the biological tillage experiment.

Block	Treatments present			
	Tall fescue	Alfalfa	Chicory	Annual Rotation
1			X	X
2			X	X
3			X	X
4		X		X
5	X	X		X
6	X	X		X

INIA Lacerta. The alfalfa was inoculated with the appropriate *Rhizobium* strain at seeding. The annual crop rotation treatment consisted of alternating wheat and barley beginning in 1993. These plots were tilled every fall, during March to May, with a crop seeded in July and harvested in December. The treatments were fertilized with nitrogen and phosphorous as required, and managed with herbicides when necessary to control weeds. The plots were mown periodically with residues left on the soil surface.

The forage treatments remained in good condition until 1999 when the experiment was overrun with bermudagrass (*Cynodon dactylon* L.), a common pasture weed. The experiment continued to be managed with periodic mowing until March 2000 when glyphosate was applied to all plots to terminate plant growth. Glyphosate was applied again in October 2000 to prepare the experiment for the seeding. Tillage was avoided to prevent soil disruption and preserve any biological tillage treatment effects from the forages.

Sorghum cv. Pioneer 8586 was selected as a test crop and was sown across all treatments on Nov 10 2000 at a rate of 15 kg ha^{-1} with 38 cm row spacing. The sorghum was fertilized with 150 kg ha^{-1} of diammonium phosphate at seeding and 100 kg ha^{-1} of urea on Jan 17 2001.

All experimental measurements were taken after the sorghum was seeded. Bermudagrass infestation continued to be a problem during the sorghum crop and was present in all plots. The sorghum crop also suffered from bird damage and there was extensive damage to the grain at harvest.

A weather station at the research station recorded precipitation and temperature during the growth of the sorghum.

4.3.2 *Crop Measurements*

Plant height of the sorghum was measured on Dec 12 2000, Jan 8 2001, and at harvest on Apr 10 2001. Eight plants per plots were randomly selected for height measurement on each date. The date of 50% panicle emergence was recorded as the date when approximately 50% of the plants within a plot had emerged panicles.

At harvest, 1 m lengths of two rows of sorghum were cut at the soil surface at three locations within each plot. The locations sampled were randomly selected from areas that were not heavily infested with bermudagrass. The panicles were removed from the harvested plants and all plant parts were oven dried to a constant weight at 60°C. Above ground dry matter was determined as the weight of the dried plant material without the panicles. The amount of bird damage to each panicle was visually estimated and a percentage of eaten grain per panicle was assigned to each sample. The estimation of grain damage was performed by the same individual on all samples. Undamaged grain was removed from the panicles and weighed to determine grain yield. The analysis of variance for grain yield was performed on the measured grain yields with the estimate of bird damage used as a covariate.

4.3.3 *Soil Measurements*

Soil water content was monitored during sorghum growth to a depth of 75 cm. Access tubes for a neutron probe were installed Nov 16 2000 with two access tubes per plot. A tube was placed at the 6 and 18 m lengths within each plot and was placed between the sorghum rows. A Trase System 6050X1 TDR probe was used to measure soil water content from 0-15 cm. Measurements were taken in close vicinity to the neutron access tubes with two TDR readings per tube. A Troxler 4302 neutron probe was used to measure water content from 15-75 cm in 15 cm increments. Soil water content was measured on the following dates: Nov 29 2000; Dec 7 2000; Dec 14 2000; Feb 13 2001; Feb 26 2001; Mar 7 2001; and Mar 14 2001.

Soil penetration resistance was measured in combination with the soil water measurements on Jan 26 2001, Feb 8 2001, Feb 13 2001, Feb 26 2001, Mar 7 2001, and Mar 14 2001. Penetration resistance was measured using a Rimik CP10 hand-held recording cone penetrometer. Penetration resistance was recorded to a depth of 45 cm in 1.5 cm increments, with six penetration profiles recorded for each plot.

Field saturated hydraulic conductivity, K_{fs}, was measured in the field from Mar 7 to 15 2001 using a Guelph permeameter. The constant head well permeameter method (Reynolds, 1993) was used to determine K_{fs} at the 2-15 cm soil depth. Two measurements were taken in each plot.

Undisturbed soil cores were removed on Mar 28 2001 for bulk density and soil water desorption measurements. Cores were 4.8 cm in diameter by 5 cm in length. Vertically oriented cores were taken at depths of 2-7 cm and 9-14 cm from two locations per plot. The soil water desorption curves were determined in the lab using a tension table and pressure plates following the procedures outlined in Topp et al. (1993). The tension table was used to determine equilibrium water contents of the cores at 0.7, 1.4, and 2.8 kPa, and the pressure plates were used for pressures of 5, 10, 20, 33, 50, and 100 kPa. The cores were oven dried to a constant weight at 105°C and bulk density determined. The oven-dried cores were crushed to pass a 2 mm sieve and water retention at 1500 kPa was determined using a 20.0 g soil sample from each core. Pore size distribution was calculated as described in McKeague et al. (1987) with pores of effective diameter >60 μm being the water retained from 0-5 kPa and 0.2-60 μm pores being the amount from 5-1500 kPa. Water content at 0 kPa was calculated from the bulk density of the cores.

Samples for wet aggregate stability analysis were collected after the harvest of the sorghum on Sep 25 2001. Samples were collected from a depth of 0 to 20 cm using a square ended spade. Soil was collected from two locations per plot and bulked. The field moist soil was sieved in the lab to obtain aggregate fractions of 4.0 to 11.1 mm and <4 mm. The samples were then dried to a constant weight at 40°C. Wet aggregate stability was measured using the wet sieving procedure described in Kemper and Rosenau (1998). The wet sieving apparatus consisted of a nest of three 12.5 cm diameter sieves with openings of 2.00, 1.00, and 0.25 mm. A 50.0 g sample was placed on the sieves and wetted by direct immersion. The sample was left undisturbed under water for 5 minutes and then sieved for 5 minutes. The sieving action had an oscillation rate of 30 cycles per minutes and an amplitude of 3.75 cm. The mean weight diameter, MWD, was calculated for each sample.

On Dec 12 2001, samples were removed from the biological tillage experiment for bulk density and texture analysis of the site. A hydraulic soil corer was used to extract sixteen cores with a diameter of 4.25 cm to a depth of 75 cm from random locations in the experiment. The cores were divided into 15 cm increments to correspond to the depths of soil water measurements. Eight of the cores were oven dried to a constant weight at 105°C for bulk density determination and the remaining eight cores were sent to the soil lab for texture determination by particle size analysis and organic matter analysis by wet oxidation. The averages for bulk density, and sand, silt, clay and organic matter contents were used to calculate predicted water holding capacities at field capacity (1500 kPa) and permanent wilting point (33 kPa) for each depth increment following the equation of Gupta and Larson (1979).

4.3.4 *Statistical Analyses*

Statistical analyses were performed on the plot means for all measured variables using the GLM procedure (SAS Institute, 1999). The model used is listed in Appendix B. Treatment differences were detected using the Type III sum of squares to account for missing values and treatment means were compared using the Fisher's protected LSD test of the treatment least-square means with a significance level of $P<0.05$.

4.4 Results and Discussion

The climate data recorded during the growth of the sorghum is shown in Figure 4.1. The sorghum growing season had a mean daily temperature of 21.8°C and received 732 mm of precipitation. The precipitation during the 2000-2001 summer growing season was greater than the historical average precipitation for La Estanzuela during this time period (Appendix A).

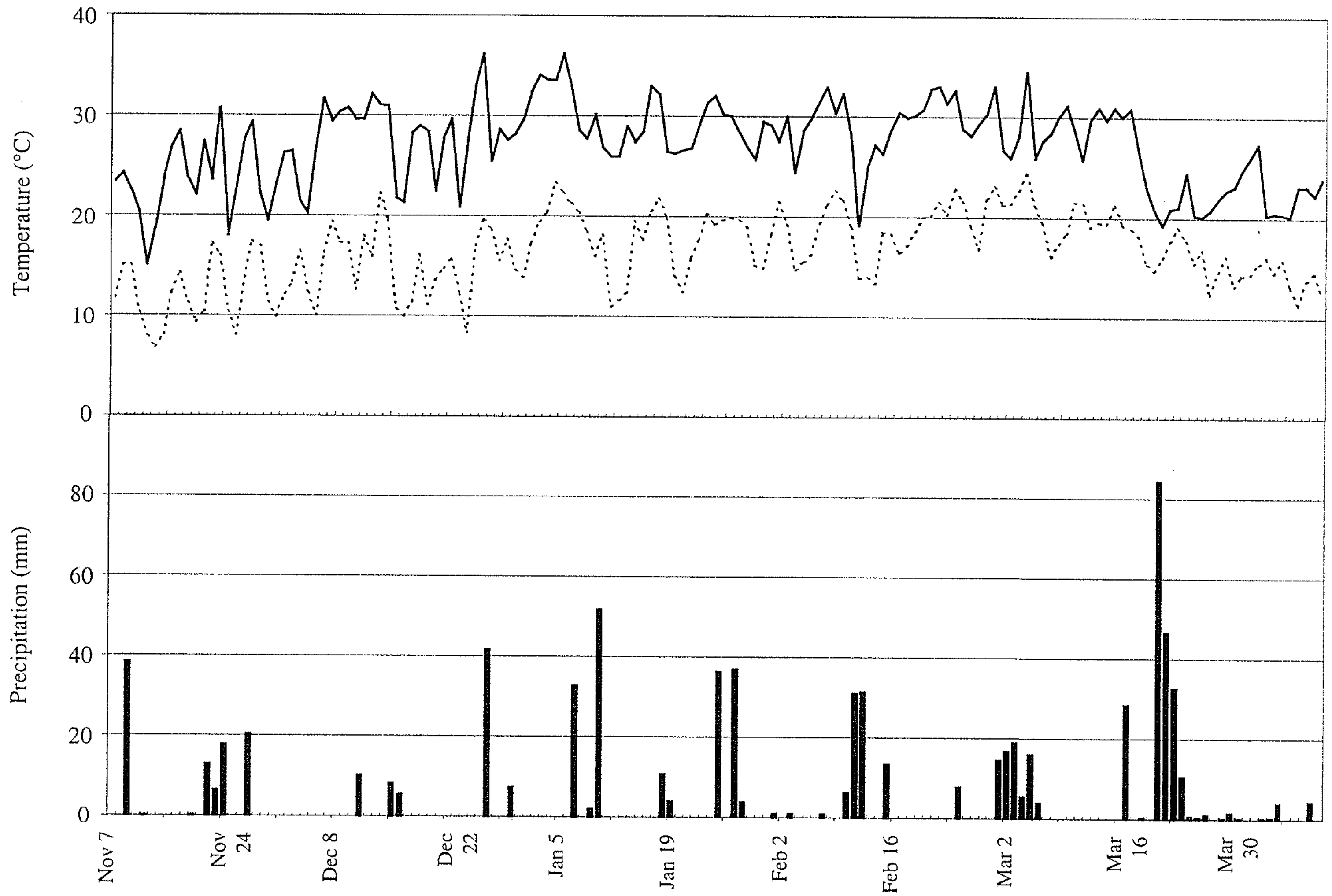


Figure 4.1. Daily temperature and precipitation during the growing season of the sorghum test crop in the biological tillage experiment. Maximum daily temperature is indicated by a solid line and minimum daily temperature by a dotted line.

4.4.1 *Crop Measurements*

Crop growth and development is greatly affected by temperature, and soil water and nitrogen availability. The nitrogen status of the treatments plots was not determined during the experiment. The value of soil testing to predict crop fertilizer requirements is limited because soil nitrogen supply to summer crops in Uruguay can be quite large and highly variable due to prevailing climatic conditions (Martino, pers. comm.). The alfalfa treatment would be expected to have higher nitrogen availability than the other treatments, because of its ability to fix nitrogen and the gradual release of this nitrogen for following crop use after the stand termination. To minimize the effect of higher nitrogen levels after alfalfa, fertilizer was applied to the sorghum in all treatments at an equal rate large enough to reduce the risk of nitrogen supply being a limiting factor for crop growth. This rate was not so large as to depress yields due to excess nitrogen. Because nitrogen availability may be greater after alfalfa, the chicory treatment was also included in the experiment, since it exhibits a taproot system that is similar to that of alfalfa (Chapter 3). Therefore, the chicory treatment can serve as a check in determining if the effects of the alfalfa treatment on sorghum growth are due to enhanced nitrogen availability or biological tillage of the root system.

The development and productivity measurements of the sorghum test crop are listed in Table 4.2. Plant height was greater in the alfalfa and chicory treatments on Jan 8 and these treatments showed earlier plant development, with less time until 50% panicle emergence. Biological tillage of certain forage crops would enhance the growth and productivity of a following crop if they enabled greater root penetration and access to soil water and nutrients. Drought stress has been shown to affect sorghum development by

Table 4.2. Height, development, and yield of the sorghum test crop in the biological tillage experiment.

Treatment	Plant Height (cm)			Date of 50% panicle emergence	Harvest	
	Dec 21	Jan 8	Apr 10		Dry matter (kg ha^{-1})	Grain yield (kg ha^{-1})
Annual rotation	24	56 b†	125	Feb 2 a	21 900	5 107
Tall fescue	17	60 b	121	Feb 2 a	20 400	3 875
Alfalfa	29	82 a	125	Jan 26 b	24 600	5 601
Chicory	32	78 a	136	Jan 26 b	26 100	5 107
p-value‡	0.23	<0.01	0.17	0.04	0.08	0.06

† Values followed by a different letter within a column are significantly different at P<0.05.
‡ p-values for the treatment comparison.

slowing the rate of development and delaying panicle initiation and flowering (Craufurd et al., 1993). The early height, and 50% panicle emergence measurements show an improvement in the development of the sorghum in the alfalfa and chicory treatments. These improvements may reflect positive changes in the soil structure of these treatments.

Treatment differences diminished by harvest, and there were no significant (P<0.05) differences in plant height, dry matter, or grain yield measurements. However, treatment effects on dry matter and grain yield measurements were significant at 0.08 and 0.06, respectively. The fact that treatment differences were not apparent at harvest may be due to the abundant precipitation received during the later half of the growing season. In February and March 2001 precipitation was 375 mm, while the historical average for this period in 238 mm (Appendix A). The improvement of plant productivity due to enhanced root growth from biological tillage would be expected to be more evident under drier conditions if extensive root exploration would be necessary to meet the crop water requirements. The crop is unlikely to have experienced water stress when considering that precipitation during the growing season was 732 mm and cumulative water use of a sorghum crop is reported to be only 550-600 mm (Kramer and Ross, 1970).

Measurements of sorghum growth and development were likely affected by the presence of bermudagrass in the experiment. This weed will have competed with the crop for water and nutrients, and may have created stress for the crop. The crop productivity measurements were further affected by the bird damage received by the grain. Using the grain yield and dry matter values reported in this experiment, the harvest index for the sorghum crop, or the ratio of kg grain to kg dry matter, was 0.21. This value is far below common grain sorghum harvest indexes of 0.38-0.58 reported for production regions in the United States, including Kansas, Missouri, Colorado, Nebraska and Texas (Vanderlip and Arkin, 1977). The grain yield values found in this experiment after the bird damage received by the sorghum offer a poor indication of crop productivity. Therefore, the dry matter measurement at harvest is a better indication of crop production than grain yield. The dry matter yields for the alfalfa and chicory treatments were higher than the tall fescue and annual rotation treatments ($P<0.10$).

4.4.2 *Soil Measurements*

The dates of soil water measurements covered a range of soil water contents during the growing season (Figure 4.2). Changes in the soil water content between sampling dates reflect water use by the sorghum crop and rehydration of the profile from precipitation. Due to the abundant precipitation at the end of the growing season and low infiltration rates of the soil, it is impossible to calculate the water use of the sorghum from soil water content measurements, since they do not account for losses due to runoff

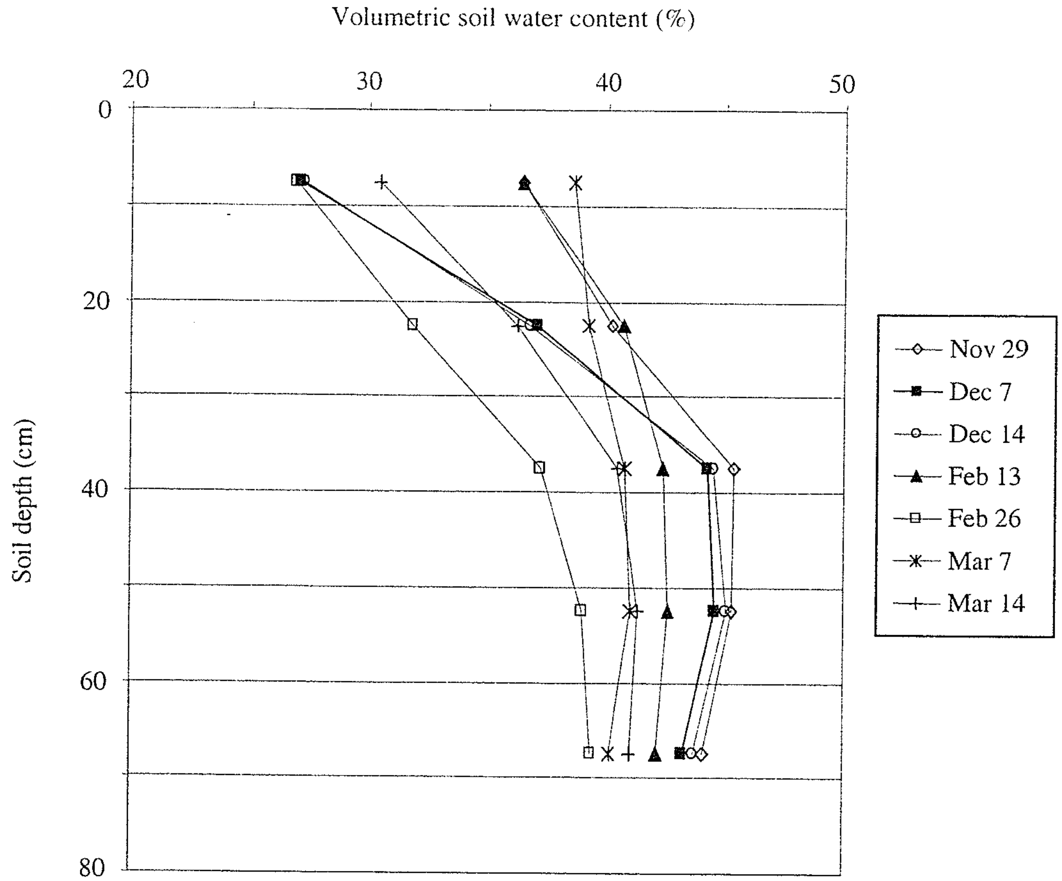


Figure 4.2. Mean soil water content profiles for each sampling date during the sorghum growing season in the biological tillage experiment.

Table 4.3. Soil physical characteristics and predicted soil water contents at permanent wilting point (PWP) and field capacity (FC) for the biological tillage experiment.

Depth	Bulk Density	Sand	Silt	Clay	Organic matter	Predicted water content† PWP	FC
(cm)	(g cm^{-3})		(%)		(%)	(vol. %)	
0-15	1.30	8	67	25	3.53	26	44
15-30	1.37	7	58	35	2.79	31	45
30-45	1.42	7	46	47	1.41	36	47
45-60	1.50	7	46	47	1.05	37	46
60-75	1.53	6	50	44	0.84	35	45

†Predicted volumetric water contents were calculated following the methods of Gupta & Larson (1979). The defining matric potentials are -1500 kPa for PWP and -33 kPa for FC.

or drainage. Predicted water contents at permanent wilting point and field capacity for the biological tillage experiment are listed in Table 4.3. The soil water contents during the sorghum growing season were within the predicted available water range and do not indicate that the sorghum crop would have experienced any water deficit stress at those times. Water content was close to the permanent wilting point at the 0-15 cm on Dec 7, Dec 14 and Feb 26, as well as at 25-30 cm on Feb 26.

The soil water content treatment means for each sampling date are shown in Figure 4.3. There were only two occurrences of significant differences between the treatments. At the 45-60 cm depth on Dec 8 the annual rotation had a lower soil water content than the forage treatments and at 30-45 cm on Dec 14 the annual rotation and tall fescue treatments had lower soil water contents than the chicory or alfalfa. These measurements were taken early in the growing season and being at lower depths, would have had little impact on crop growth. The equal plant heights among the treatments on Dec 21 (Table 4.2) would indicate there were no differences in plant growth up to that point in the growing season.

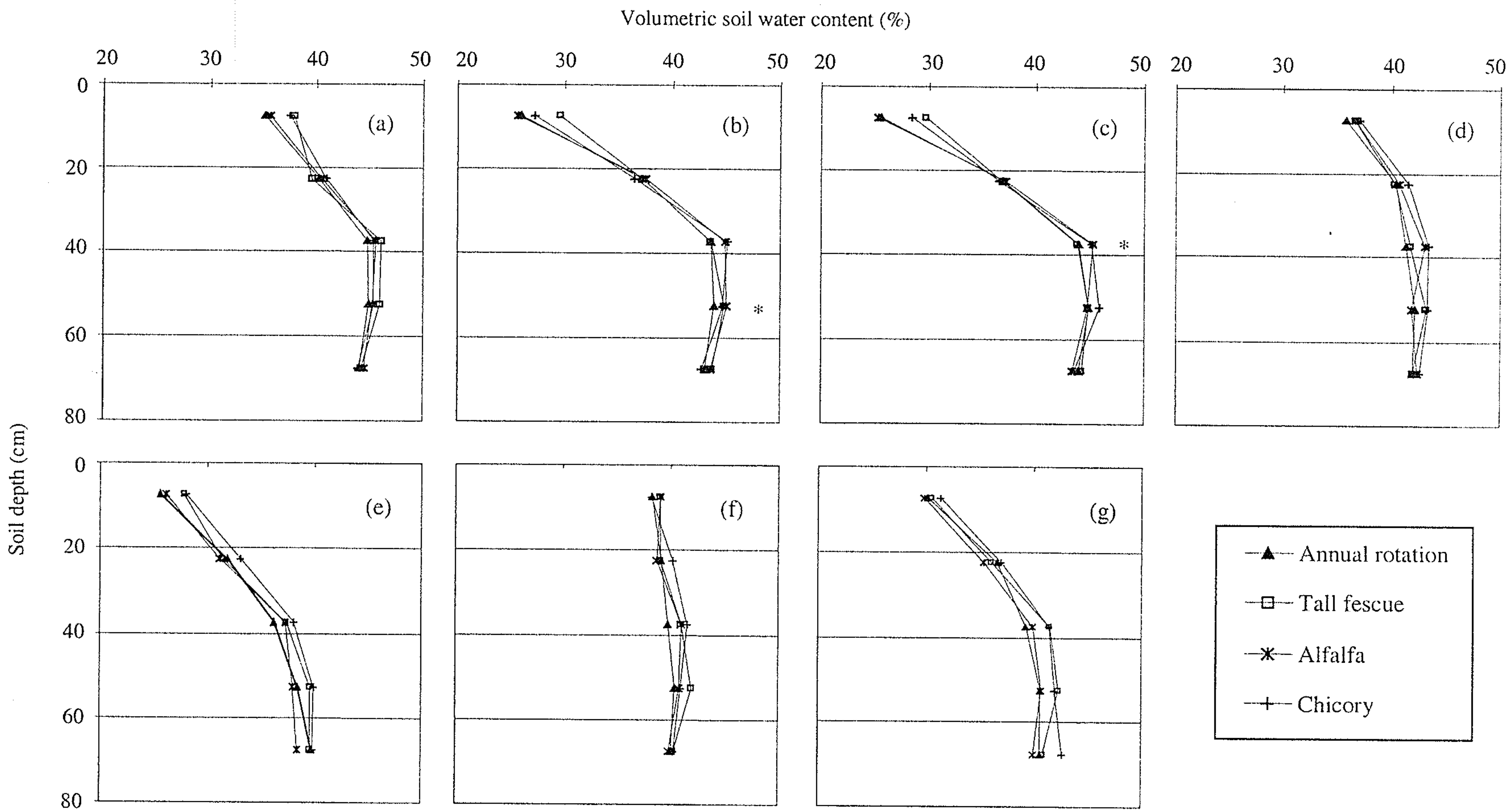


Figure 4.3. Soil water content profiles at different sampling dates during the sorghum growing season in the biological tillage experiment. (a) Nov 29; (b) Dec 8; (c) Dec 14; (d) Feb 13; (e) Feb 26; (f) Mar 7; (g) Mar14. Soil depths with significant ($P<0.05$) treatment differences within a sampling date are marked with an asterisk (*), otherwise treatment effects were non-significant.

The soil penetration resistance profiles also covered a wide range of values (Figure 4.4). The variation between sampling dates reflects the differences in soil water content between each date. Feb 8 and Feb 26 represent drier soil conditions, whereas Feb 13 and Mar 7 represent wet profiles after a period of precipitation.

Soil penetration resistance was a highly variable property and there were few significant differences between treatments on each sampling date (Figure 4.5). The only observed trend was significantly lower penetration resistance in the chicory treatment around 20 cm on the two wetter dates. On Feb 13, the chicory had significantly lower penetration resistance at depths of 19.5-24.0 cm than the annual rotation and tall fescue treatments. On Mar 7, penetration resistance in the chicory treatment was lower than all other treatments at the 18.0-22.5 cm depth. These differences are likely due to higher water contents in the chicory treatment, though not significantly so, at these depths and dates. These two sampling dates both follow a period of rainfall where there was 68.6 mm of precipitation on the three days prior to Feb 13 and 75.5 mm on the six days before Mar 7 (Figure 4.1). Lower penetration resistance around 20 cm in the chicory treatment, due to higher soil water content, may indicate improved water infiltration and movement within the soil profile in this treatment. The lower soil strength could be reflective of biological tillage and an improved network of water moving pores in the chicory treatment.

The critical value of soil strength at which root growth is limited is commonly cited as 2.0 MPa (da Silva et al., 1994; Martino and Shaykewich, 1994; Ishaq et al., 2001). Penetration resistances of 2.0 MPa or higher were found throughout most of the profile on Feb 8 and Feb 26. These sampling dates both followed periods of little rainfall

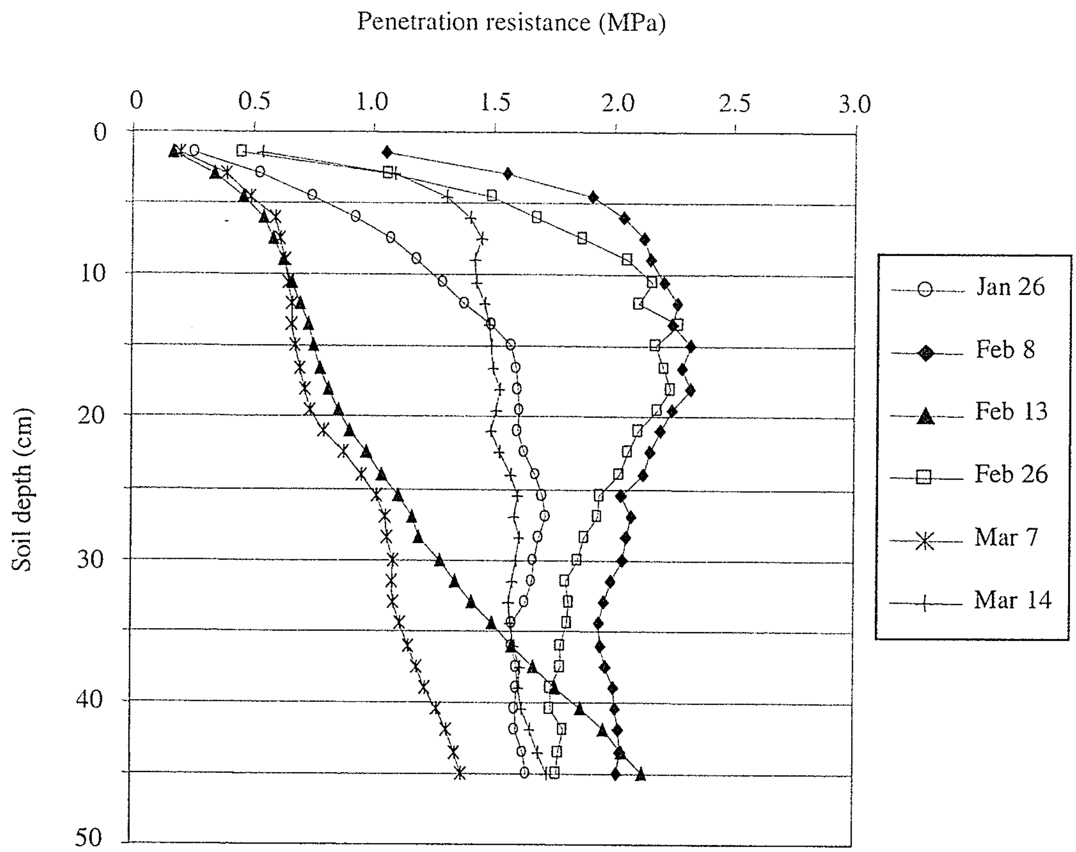


Figure 4.4. Mean penetration resistance profiles for each sampling date during the sorghum growing season in the biological tillage experiment.

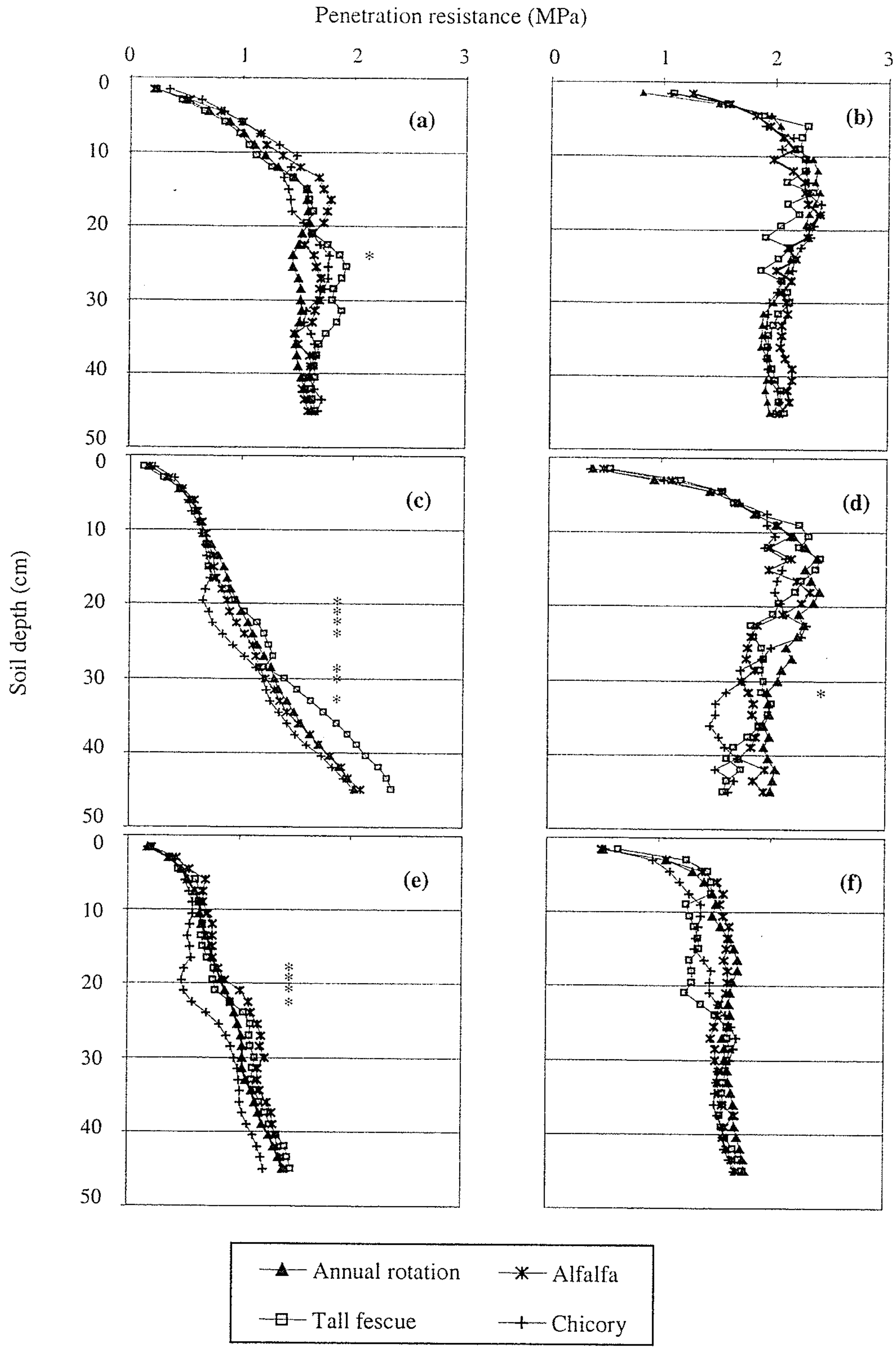


Figure 4.5. Penetration resistance profiles at different sampling dates during the sorghum growing season in the biological tillage experiment. (a) Jan 26; (b) Feb 8; (c) Feb 13; (d) Feb 26; (e) Mar 7; (f) Mar 14. Soil depths with significant ($P<0.05$) treatment differences within a sampling date are marked with an asterisk (*), otherwise treatment effects were non-significant.

with less than 8 mm of precipitation in the previous 10 days. Feb 26 had the lowest soil water content of all soil water sampling dates. The soil water content on Feb 26 was within the predicted available water range, but the high soil strengths on this date would likely have limited root growth. These high soil strength values under low soil water contents indicate that root growth may be limited in this soil even within the normally accepted water content range. Looking at the precipitation pattern during the sorghum growing season, there may have been other periods during late December or January in which the crop experienced similarly dry conditions and periods of limiting soil strength.

Hydraulic conductivity in saturated soil is affected by the pore geometry of the soil, or the size and continuity of the pore system, and can be useful for characterizing changes in macroporosity (Reynolds, 1993). There were no treatment differences in the K_{fs} of the treatments for the 2-15 cm depth as the p-value for the treatment comparison was 0.38. The measured values for each of the treatments were 6.4, 10.5, 5.8, and 9.8 cm day^{-1} for the annual rotation, tall fescue, alfalfa and chicory treatments, respectively. Rasse et al. (2000) found that alfalfa roots increased saturated hydraulic conductivity in the top 8 cm by 57% after 2 years, in comparison to bare fallow and this was associated with corresponding increases in total porosity and macroporosity. In a 6 yr study comparing the effects of several forage amelioration treatments, the highest saturated hydraulic conductivities for the upper 20 cm were found in the treatments with the highest earthworm populations, root densities, and aggregate stabilities (Francis et al., 1999).

Hydraulic conductivity was only measured in the surface 15 cm in this experiment. The tillage practiced in the annual rotation may have been adequate to create similar pore quantities as the forage roots, though these may not be as stable as root-formed pores. The bermudagrass roots would also have influenced this region in the soil profile. Bermudagrass roots would have been abundant in the upper soil layer and influenced pore size and continuity in this region, thereby concealing treatment differences. Hydraulic conductivity was also measured during the growth of the sorghum and plant roots from the sorghum and bermudagrass growing within pores would have blocked rapid water flow. A better indication of the pore structure in the treatments would have been a measure of saturated hydraulic conductivity prior to seeding the sorghum crop.

The water desorption curves constructed from the undisturbed cores taken at 2-7 and 9-14 cm are shown in Figure 4.6. The water retained at a given soil suction is influenced by soil texture and structure, with water held at low suctions being predominantly affected by structure and water held at high suctions being determined by texture. The curves are similar among all of the treatments. The lack of treatment differences in the water held at each soil suction, indicate that pore structure was similar among all of the treatments.

Water desorption curves can also be used to calculate pore distribution. Values for pore size distribution are listed in Table 4.4. There were no treatment differences between the distribution of macropores, those with effective diameters >60 μm, or the distribution of micropores that store available water, 0.2-60 μm diameters. The lack of differences in the distribution of macropores agrees with the saturated hydraulic conductivity measurements, in which there was no difference among treatments in the rate of water flow.

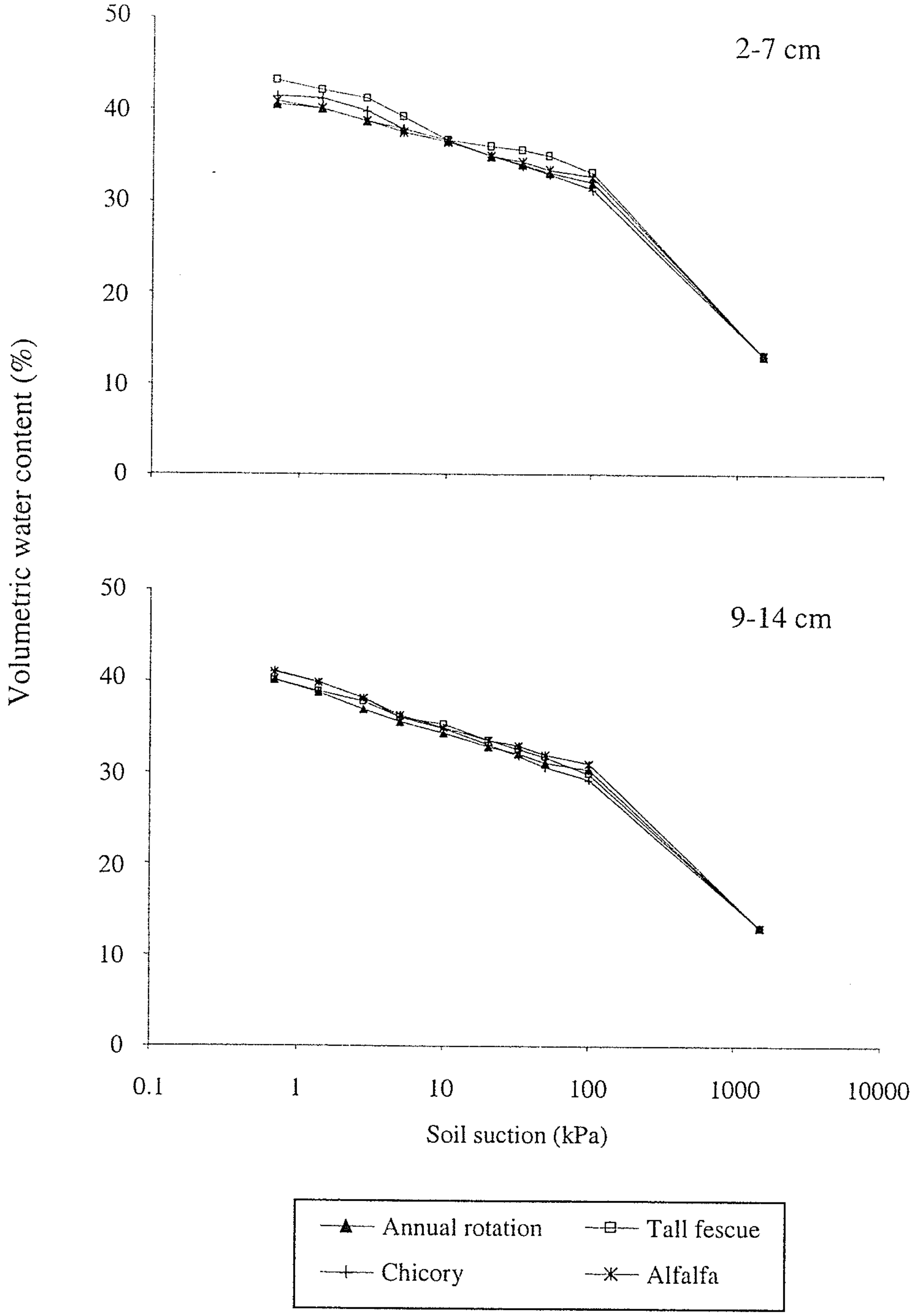


Figure 4.6. Soil water desorption curves for two depths in the biological tillage experiment.

Table 4.4. Treatment least-square means for bulk density, and pore distributions of >60 and 0.2-60 μm effective diameter pores for the biological tillage experiment.

Treatment	Bulk density ($g\ cm^{-3}$)	Pore distribution (%) >60 μm	Pore distribution (%) 0.2-60 μm
		2-7 cm	
Annual rotation	1.28	13.8	24.7
Tall fescue	1.20	15.7	26.0
Alfalfa	1.29	14.0	24.4
Chicory	1.25	15.0	24.6
p-value†	0.23	0.63	0.35
		9-14 cm	
Annual rotation	1.32 a‡	14.6	22.6
Tall fescue	1.23 b	17.6	23.0
Alfalfa	1.30 a	14.6	23.3
Chicory	1.30 ab	14.9	22.9
p-value	0.05	0.20	0.48

† p-values for the treatment comparison.
‡ Values followed by a different letter within a column are significantly different at $P<0.05$.

There were treatment effects on the bulk density of the 9-14 cm cores (Table 4.4). The tall fescue treatment decreased bulk density compared to the annual rotation and alfalfa treatments. Increasing the pore space or organic matter in the soil can decrease bulk density values. Tall fescue has high root numbers and root biomass in the surface soil (Chapter 3), which may have contributed to the lower bulk density values for this treatment.

The values for wet aggregate stability are listed in Table 4.5. Treatment differences were not significant in either aggregate fraction with average MWDs of 1.04 and 3.20 for the <4.0 and 4.0-11.1 mm aggregate fractions, respectively. There have

Table 4.5. Mean weight diameter of water stable aggregates for two aggregate size fractions in the biological tillage experiment.

Treatment	Mean weight diameter (mm)	
	<4.0 mm aggregates	4.0-11.1 mm aggregates
Annual rotation	1.03	3.07
Tall fescue	1.25	3.70
Alfalfa	1.03	2.69
Chicory	0.84	3.34
p-value†	0.41	0.11

† p-values for the treatment comparison.

been many studies showing an increase in aggregate stability and MWD under forage crops or rotations including forages (Haynes et al., 1991; Francis et al., 1999; Rasse et al., 2000). Improvements in aggregate stability are generally associated with increase in organic matter. In a study comparing the aggregation of several forage species, Stone and Buttery (1989) found that increases in wet aggregate stability were correlated with organic carbon, and the species showing the greatest improvements were those with the highest root dry weight. The lack of differences in aggregate stability is in agreement with the finding that there were no differences in total organic carbon found between the treatments in the biological tillage experiment.

4.4.3 *General Discussion*

The presence of bermudagrass in this experiment would have influenced all of the variables measured in this study. The grassy weed would have competed with the sorghum crop for water and nutrients, thereby affecting growth and productivity parameters. The fibrous roots of this grass species would also have been abundant in the soil, as was evident from visual observations of the experiment, and would have altered the soil physical properties by performing biological tillage of its own. The bermudagrass would have concealed treatment effects and may have been responsible for the lack of treatment differences in most of the properties measured. If the actions of the bermudagrass did neutralize any treatment effects, this may imply that any treatment effects were either small in magnitude, or did not last very long after treatment termination. The persistence of any soil structure improvements by forage crops would be important for determining the length of each rotation phase in a mixed cropping system. It would be valuable to repeat this study under less weedy conditions and current attempts are being made to eradicate the bermudagrass and reestablish the experiment.

Aside from the weed influences, the absence of treatment effects on most of the properties examined in this study was also due to the high variation observed for each of the parameters. As well, treatment effects were not always consistent across all measured parameters. For example, in the penetration resistance profiles chicory showed lower penetration resistance under wet conditions, which could indicate improved water movement within the profile. However, the chicory treatment did not show a similar improvement in the hydraulic conductivity, water desorption curve, or distribution of macropores, all of which serve as indicators of water flow in the soil. Both the chicory and alfalfa treatments had positive effects on the early growth and development of the sorghum crop, but reasons for this improvement, based on the physical condition of the soil, were not clear from the properties measured. The improved productivity in the these treatments may have been due to another factor other than the soil physical properties, such as soil nutrient content. Nutrient analysis was not performed in this study and though it may be anticipated that nitrogen content would be higher in the alfalfa treatment, due to nitrogen fixation, there is no apparent reason why nitrogen in the chicory treatment would differ from the annual rotation or tall fescue treatments.

Most of the soil physical properties measured in this experiment were restricted to the surface 20 cm of the soil, with soil water being measured to 75 cm and penetration resistance to 45 cm. Improvements to soil physical properties have generally been associated with increases in soil organic matter in the areas of the soil profile with the greatest root abundance (Stone and Buttery, 1989; Francis et al., 1999). The forage species used in this experiment have been shown to have a large proportion of their root biomass located in the upper 20 cm of the soil profile under similar soil conditions (Chapter 3). However, roots have been observed as deep as 90-100 cm. When significant treatment differences occurred in the penetration resistance profiles, they were at depths of 20 cm or greater. Forages may benefit following grain crops by forming biopores in the subsoil. Increased organic matter in the 20-60 cm range has been found under a long-term pasture-arable rotation (Chapter 5), which is evidence of greater root growth deeper in the soil profile in a mixed cropping system than an annual crop rotation. Further study on the biological tillage effects of forages in Uruguay would be benefited by an examination of soil properties below 20 cm.

4.5 Conclusions

A study was conducted in southwestern Uruguay to examine the biological tillage of 7 year forage stands of tall fescue, alfalfa and chicory. Early growth and development of a grain sorghum test crop showed increased plant height and earlier plant development in the chicory and alfalfa treatments. There were no differences in crop productivity at harvest, which may have been due to the abundant precipitation and lack of moisture stress during the growing season studied. Measurements of soil physical properties showed reduced soil strength around 20 cm in the chicory treatment under wet soil conditions, and decreased bulk density at 9-14 cm in the tall fescue treatment. Biological tillage of the forage species in improving soil physical properties or following crop productivity was not clearly evident in this study. Weed infestation by bermudagrass would have affected the results of all measured parameters. The role of forages in performing biological tillage in Uruguay needs further study and the measurement of soil properties below 20 cm is recommended.

5. CARBON ALLOCATION OF FORAGES

5.1 Abstract

Interest is increasing in management practices that can accumulate soil organic carbon levels as a step to mitigate climate change. Physical fractionation was used to study the carbon allocation of forages in Uruguay. An experiment of short duration yielded little difference in soil organic carbon between forage treatments and an annual crop rotation. The 7 yr forage stands did have greater coarse particulate organic carbon at a depth of 0-7.5 cm, which represents the youngest carbon fractions and was more responsive to management practices. A 38 yr rotation study showed higher organic carbon in all size fractions for a rotation of pasture with annual grain crops, than an annual crop rotation, at depths of 20-40 and 40-60 cm. These differences in carbon may have been due to greater carbon additions at depth from the forage crops, and indicate that the subsoil contributed to carbon sequestration in these soils.

5.2 Introduction

Due to global concern surrounding climate change and increased CO_2 levels in the atmosphere, there has been much research interest in the potential for agricultural soils to sequester carbon. The concept of carbon farming and farmers receiving economic benefits for management practices that sequester carbon is gaining interest in Uruguay. Incorporating forage crops in rotations is one strategy that has increased soil organic carbon levels (Chan, 1997; Campbell et al., 1997; Paustian et al., 1997a; Chan et al., 2001).

The use of physical fractionation procedures has allowed the separation of organic carbon into meaningful fractions that differ in size, extent of decomposition, and stability

(Christensen, 2001). Cambardella and Elliot (1992) separated soil organic carbon based on size, with particles >53 μm forming the particulate fraction and particles <53 μm forming the mineral fractions. They found that the particulate fraction was more responsive to changes in management than the mineral fraction, which represented a more stable or sequestered carbon pool. The particulate organic carbon fraction has been used as an early indicator of changes in soil organic carbon levels (Chan et al., 2001).

Previous research has focused on organic carbon levels in the surface layers. Organic carbon levels decrease with depth as carbon inputs from root biomass and crop residues decrease. However, perennial forages have the ability to develop a more extensive root system than annual crops because of the continued growth of their root systems over several years (Weaver, 1926). If forage roots develop more root biomass deep in the soil profile, then they may be able to increase organic carbon levels below the surface layers.

The influence of forages on soil organic carbon in Uruguay was studied in two experiments. The objective of the first experiment was to compare the soil organic carbon levels between three forage species and an annual crop rotation. The second experiment was used to determine the long-term effect of a crop rotation containing pasture on the level of soil organic matter found at 20-60 cm in the soil profile.

5.3 Materials and Methods

5.3.1 *Experiment Descriptions*

Two experiments at the INIA La Estanzuela research station in southwestern Uruguay were selected for soil organic carbon analysis.

An experiment designed to assess the biological tillage effects of forage species was initiated in 1992 and has been previously described (see Chapter 4). This experiment was sampled on May 29 2001 and treatments consisted of the tall fescue, alfalfa, chicory, and annual rotation plots. Eight soil subsamples per plot were taken and bulked from depths of 0-7.5, 7.5-15, and 15-30 cm.

The second experiment was a long-term rotation experiment initiated in 1963. This experiment was designed to evaluate seven cropping systems that differ in the amount of time under pasture. The two treatments selected for sampling were an annual crop rotation and a rotation with alternating cycles of annual grain cropping and pasture. Plots are 25 × 200 m and are situated lengthwise on a 2-4% slope. All treatments were randomized within three field blocks. A plot diagram for the long-term rotation is illustrated in Figure 5.1.

Twice there were modifications made to the long-term experiment. In 1974, the treatments maintained the same cropping sequences but the rotation year was staggered for the three blocks. Therefore, each field block represents a different phase of the rotation. This was to account for yearly climatic differences on crop productivity. In 1983, the cropping sequences were altered to reflect changes in technology and farmer crop preference that had occurred during the previous 20 years. Prior to 1983, the annual crop rotation consisted of a 4 yr cycle of sorghum-flax (*Linum usitatissimum* (L.) Griesb.)-wheat-sunflower, and the pasture rotation was composed of a 4 yr cycle of the same annual crops and 4 yr of pasture. After the cropping sequence changes, the annual rotation became a 3 yr rotation of sorghum-barley,sunflower-wheat. The sunflower in the second year is seeded as a second crop after the harvest of the barley. The pasture

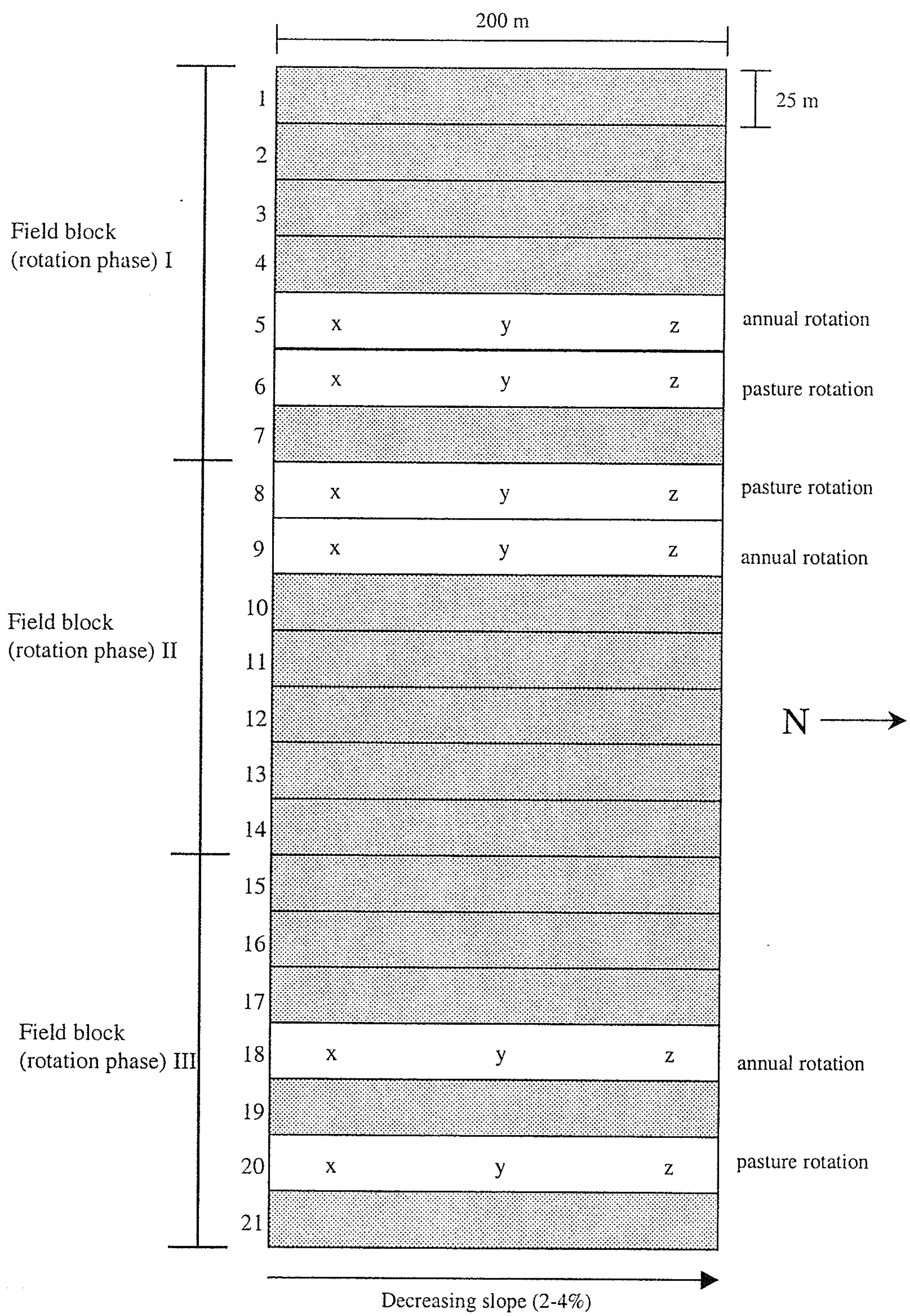


Figure 5.1. Plot diagram of the long-term rotation experiment. The three sampling locations (blocking factor) for each plot (treatment factor) are labeled as: x = upper-slope, y = mid-slope, z = toe-slope.

rotation adopted the same annual cropping sequence, except that the pasture was undersown in the final wheat crop, and the pasture phase lasts for 3 yr. The crop rotation histories from 1984 to the date of sampling for the plots of the annual and pasture rotations are listed in Appendix C.

The pasture phase consists of a grass-legume mixture and is composed of tall fescue, white clover (*Trifolium hybridum* L.), and birdsfoot trefoil. Fertilizer application varies according to the crop being grown and soil testing. On average the treatments receive 40 kg P_2O_5 ha^{-1} yr^{-1} each year and 40 kg N ha^{-1} yr^{-1} when annual crops are grown. Therefore the pasture rotation only receives nitrogen fertilizer during the annual cropping phase. The annual crops are harvested for grain and the grain is removed. The pasture phases are cut to simulate grazing and all forage residues are returned to the plots.

The long-term rotation experiment was sampled for organic carbon on Dec 3 2001. The three field blocks, or rotation phases, of the annual rotation were bare soil about to be sown to sorghum, wheat, and sunflower. The phases of the pasture rotation were bare soil about to be sown to sorghum, 3rd yr pasture, and 2nd year pasture. Samples were removed from three locations in each plot comprising the upper-, mid-, and toe-slope positions at approximately the 30, 100, and 170 m distances. Eight subsamples were collected and bulked for each location from depths of 20-40 and 40-60 cm.

5.3.2 *Lab Analyses*

Soil samples taken from the field were broken up to pass through a 2 mm sieve and dried to a constant weight at 45°C. Samples were stored at approximately 5°C until they were processed in the lab. Carbon fraction analysis was performed in the lab based the physical fractionation technique described by Cambardella and Elliot (1992). A 3.33

g subsample of soil was dispersed in 10 mL of sodium hexametaphosphate solution by shaking for 16 h on a reciprocal shaker. The dispersed samples were passed through two sieves, sized 212 and 53 μm. The material remaining on each of the sieves represented the 212-2000 and 53-212 μm size fractions, respectively. The organic carbon contents for each size fraction was determined by wet oxidation with $K_2Cr_2O_7$ and correspond to the coarse particulate organic carbon, POC, and fine POC fractions, respectively. Total organic carbon, TOC, was determined by wet oxidation of a separate subsample and the mineral associated organic carbon, MAOC, was calculated as the difference between TOC and the two POC fractions. The MAOC corresponds to the <53 μm size fraction.

5.3.3 *Statistical Analyses*

Statistical analyses were performed on all carbon variables using the GLM procedure in the SAS statistical software (SAS Institute, 1999). The statistical model used is described in Appendix B. Values for each depth were analysed separately. Mean comparisons for the biological tillage experiment were done with a Fisher's protected LSD test of the treatment least-square means. The long-term rotation experiment was analysed as a randomized complete block design with sampling location as the blocking factor and each plot, or rotation phase, as a treatment. A contrast statement of the annual vs. pasture rotation plots was used to determine differences in carbon levels between the two rotations.

5.4 Results and Discussion

5.4.1 *Biological Tillage Experiment*

The values for total organic carbon and the three size fractions from the biological tillage experiment are presented in Table 5.1. The amount of organic carbon decreased

Table 5.1. Least-square means for total organic carbon (TOC), coarse particulate organic carbon (POC), fine POC, and mineral associate organic carbon (MAOC) at three depths in the biological tillage experiment.

Treatment	TOC	Coarse POC	Fine POC	MAOC
	g C kg^{-1} soil			
			0-7.5 cm	
Annual rotation	23.9	1.7 a†	2.0	20.2
Tall fescue	25.5	2.7 b	2.1	20.7
Chicory	27.2	2.3 b	2.9	22.0
Alfalfa	25.9	2.1 b	2.1	21.7
p-value‡	0.11	0.02	0.19	0.40
			7.5-15 cm	
Annual rotation	22.2	0.9	1.4	19.9
Tall fescue	23.2	1.1	1.3	20.8
Alfalfa	23.1	1.0	1.4	20.6
p-value	0.49	0.18	0.58	0.51
			15-30 cm	
Annual rotation	20.3	0.6	0.9	18.8
Tall fescue	19.9	0.9	0.8	18.2
Alfalfa	20.6	0.6	0.9	19.1
p-value	0.91	0.16	0.81	0.85

† Values followed by a different letter within a column are significantly different at P<0.05.
‡ p-values for the treatment comparison.

with depth with an average of 25.6 g C kg^{-1} soil in the upper 7.5 cm and 20.3 g C kg^{-1} soil at 15-30 cm. Carbon inputs from root biomass and crop residues would be expected to decrease within the soil profile and influence the distribution of organic carbon with depth.

The POC fractions accounted for 17, 10, and 8% of the total organic matter present in the 0-7.5, 7.5-15, and 15-30 cm depths, respectively. Other reported values for the proportion of POC range from 14% under an annual cropped system to 56% under permanent pasture (Chan, 1997). The low POC fraction in the biological tillage experiment may reflect the long period of annual cropping and cultivation the site received before initiation of the experiment. Chan (2001) found that the sodium hexametaphosphate used to disperse soil samples prior to fractionation dissolves 4-19% of the organic carbon. This would lead to an underestimation of POC and overestimation of MAOC.

The only significant difference in organic carbon found between the four treatments was in the coarse POC fraction at the 0-7.5 cm depth. The three forage treatments all had a greater amount of coarse POC than the annual cropping treatment, with an average difference of 0.7 g C kg^{-1} soil. This implies a greater addition of crop residues or root biomass in the surface layer, since the coarse POC fraction represents the organic matter derived from recently added residues, or a decrease in the decomposition rate of POC with the forage treatments.

The lack of treatment differences may have been due to the short duration of the treatments and the long period between forage termination and carbon sampling. The forage plots lasted for 7 yr and were terminated 14 months before samples were taken for carbon analysis. Recently added carbon would be fairly labile and could have been lost after the end of the forage stands. A more likely reason for the lack of treatment differences is the presence of bermudagrass in the biological tillage experiment. Roots from the grass would have been increased carbon inputs to the soil where the weed was present. Organic carbon additions by the bermudagrass would have concealed differences between the experimental treatments. Carbon sequestration by the bermudagrass likely had a greater influence on reducing treatment effects than any loss of carbon during the period between forage termination and date of carbon sampling.

The effects of management changes on soil carbon are expected to occur slowly and would be more evident in an experiment of longer duration (Paustian et al., 1997b). For this reason, POC fractions are used as indicators of changes in soil organic carbon. The increase in coarse POC under forages in the 0-7.5 cm depth may be an early indicator that soil organic carbon will increase with the use of forage crops.

5.4.2 *Long-Term Rotation Experiment*

The mean organic carbon contents for the two rotation treatments are shown in Figure 5.2. The level of organic carbon decreased with depth, which is likely due to a reduction of carbon inputs from root matter with depth. A decline in root biomass with depth is supported by the observations of forage roots (Chapter 3). The two POC fractions made up an average of only 6% of the total organic carbon for both of the treatments and depths. The physical fractionation procedure used may cause the amount of POC to be underestimated due to the use of sodium hexametaphosphate.

The differences between the rotations were significant in all carbon fractions for both depths, as the p-values for the contrast statements show in Figure 5.2. The rotation that included a pasture phase had higher levels of organic carbon in each size fraction. The greater organic carbon content in this rotation may have been due to greater carbon inputs at depth from the roots of forage species than those of annual crops. As well, if forages perform biological tillage they may increase the rooting depth of subsequent

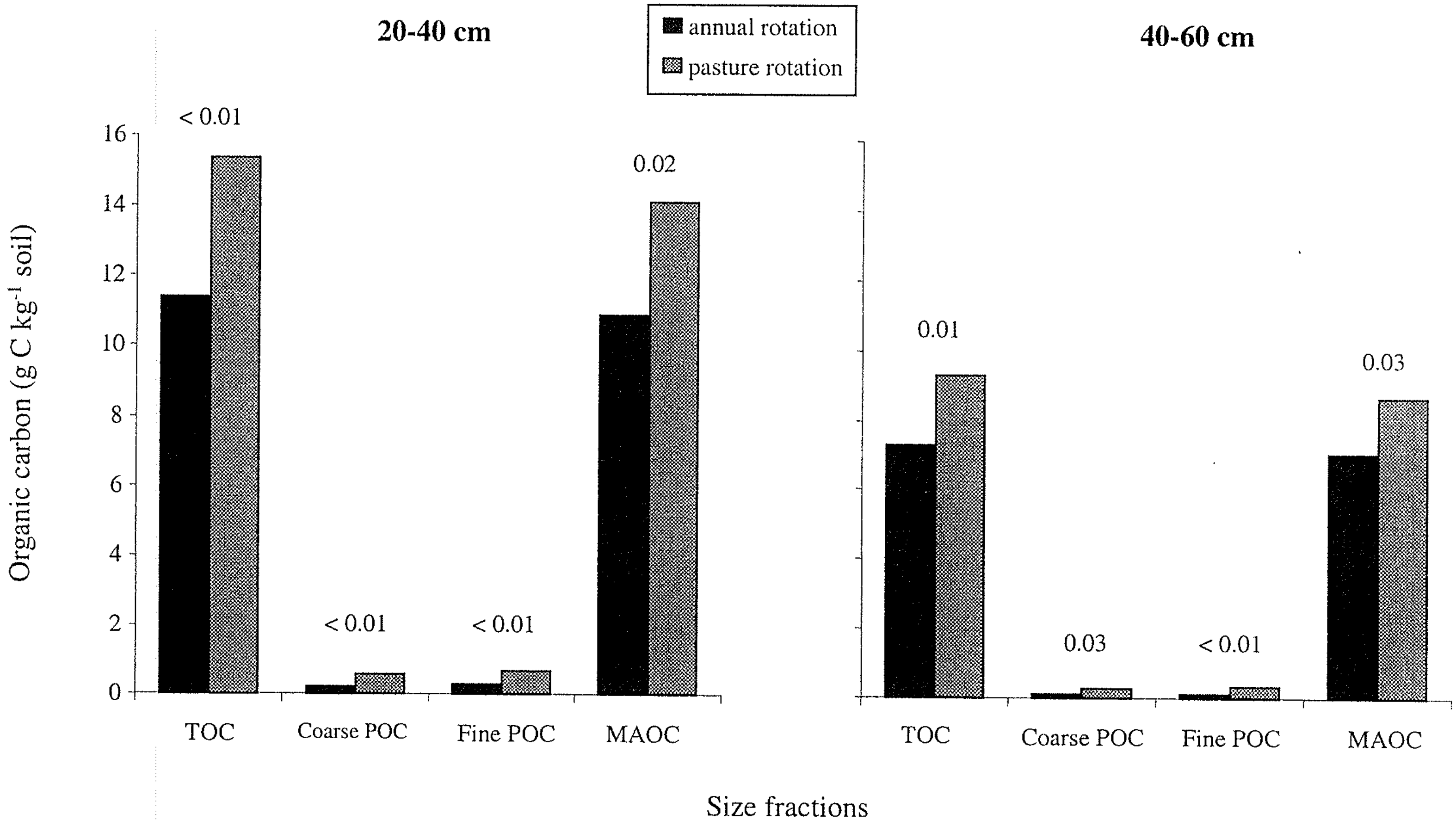


Figure 5.2. Total organic carbon (TOC), coarse particulate organic carbon (POC), fine POC, and mineral associate organic carbon (MAOC) at two depths in the long-term rotation experiment. The p-values for the rotation contrast statement are presented for each comparison.

annual crops, which would contribute to greater carbon inputs at depth in the pasture rotation.

At the 20-40 cm depth, there was 4.0 g C kg^{-1} soil more total organic carbon in the pasture rotation than in the annual rotation. The difference in the MAOC fraction accounted for 81% of the difference in total carbon. The MAOC fraction, which represents the stable or sequestered carbon (Cambardella and Elliot, 1992), was 3.2 g C kg^{-1} soil greater in the pasture rotation. Assuming a bulk density of 1.40 g cm^{-3} (based on the bulk density values found for the biological tillage experiment (Table 4.3), which was situated close to the long-term rotation), this is equivalent to 8960 kg C ha^{-1} (Table 5.2). The pasture rotation had 1.9 g C kg^{-1} soil greater organic carbon at the 40-60 cm depth. The MAOC fraction was responsible for 80% of the difference in total organic carbon. At this depth the difference in the stable carbon fraction was 1.6 g C kg^{-1} soil or 4740 kg C ha^{-1} (with a bulk density of 1.48 g cm^{-3}).

For both depths, the POC fractions were an average of 2.5 times greater in the pasture rotation than the annual rotation. The TOC in the pasture rotation was 1.4 times the level in the annual rotation. The POC fractions showed a greater difference between the two management treatments than TOC. This supports other findings that POC is more sensitive to changes in management and can act as an early indicator of changes in TOC (Cambardella and Elliot, 1992; Chan et al., 2001).

The rotation treatments may differ in bulk density at the depths sampled. This property was not measured in the long-term rotation experiment, and there are no references in the literature for bulk density values at these depths under different rotation treatments. A lower bulk density under the pasture rotation treatment, due to increased

Table 5.2. Carbon levels for total organic carbon (TOC), coarse particulate organic carbon (POC), fine POC, and mineral associated organic carbon (MAOC) in the long-term rotation experiment as expressed on an area basis using various assumed values of bulk density (BD).

Treatment	Assumed BD	TOC	Coarse POC	Fine POC	MAOC
	g cm^{-3}	kg C ha^{-1}			
			20-40 cm		
Annual rotation	1.40	31 920	644	812	30 520
Pasture rotation	1.40	43 120	1 652	1 932	39 480
	1.30	40 040	1 534	1 794	36 660
	1.20	36 960	1 416	1 656	33 840
			40-60 cm		
Annual rotation	1.48	21 608	266	385	21 016
Pasture rotation	1.48	27 528	829	1 006	25 752
	1.38	25 668	773	938	24 012
	1.28	23 808	717	870	22 272

root channels, soil organic matter, or other factor, would negate some of the difference in organic carbon when the amount of carbon present is considered on an area basis. However, the difference in the carbon levels of each fraction would still be considerable with a difference in bulk density of 0.2 g cm^{-3} (Table 5.2). For example, the TOC fraction is 1.2 times and 1.1 times greater in the pasture rotation than the annual rotation at 20-40 and 40-60 cm, respectively, when the difference in assumed bulk density is 0.2 g cm^{-3}.

Previous work on the soil organic matter dynamics of the 0-20 cm layer in this same long-term rotation experiment has shown a decrease in soil organic matter in both rotations during the first 27 yr of the experiment, though the rate of decrease in the pasture rotation was less than in the annual rotation (Díaz, 1992). Soil erosion was thought to have a predominant influence on the soil organic matter content at this depth. Though carbon dynamics in the surface soil are confounded by soil erosion, these processes will impact less on the carbon content of the subsoil layers. Soil erosion will affect the organic carbon content of the subsoil only by slowly lowering the reference depths within a soil profile over a long period of time. For example, if more topsoil is removed in the annual rotation treatment than in the pasture rotation, then a measurement taken at 20-40 cm will be composed of soil that initially originated lower in the profile in the annual rotation. However, the loss of soil in the long-term rotation experiment was only in the range of 0.3-1.9 mm yr^{-1} (García, 1992) and soil forming processes are continually ongoing within the profile. Therefore, the impact of soil erosion on organic carbon concentrations in the subsoil is expected to be minimal.

Landscape position within the treatment plots was used as a blocking factor for field sampling and statistical analysis in this experiment. Landscape position might be expected to influence soil organic carbon levels as it affects water movement and availability within the soil profile, and soil erosion and deposition processes. However, the block effect was not found to be significant for any of the variables or depths measured. As previously discussed, erosion processes will have had little impact on subsoil layers. In a humid climate, such as that in Uruguay, landscape position may have less effect on soil hydrology and plant growth due to abundant soil water during the growing season. If landscape position did not significantly influence crop growth, it would not have affected carbon deposition and soil organic carbon levels.

5.4.3 *General Discussion*

Soil fractionation procedures were developed to find carbon fractions that were more responsive to management changes than total organic carbon, and to separate organic carbon into the theoretical pools represented in soil organic matter models (Carter and Gregorich, 1996; Christensen, 2001; Chan, 2001). The results of these experiments confirm that POC can be used as an early indicator for changes in total soil organic matter content, as differences in POC were greater than those for TOC in both the biological tillage and long-term rotation experiments. The POC fraction represents recently added organic carbon. Increases in the POC indicate that new carbon is being added to the soil and in time, the TOC of the soil will likely increase if the management practice is maintained. The POC can be used as a qualitative indicator of changes in soil organic carbon.

The MOAC fraction, which represents the stable, sequestered carbon showed significant effects of rotation practice after 38 yr in the long-term rotation experiment. This is still a relatively short time period in terms of organic matter dynamics and would more accurately describe the slow pool, with a turnover rate of decades, than the passive pool, with a turnover rate of hundreds to thousands of years, as described in the model by Parton el al. (1987). Physical fractionation procedures that use a combination of size, density, or aggregate separations such as those used by Golchin et al. (1994) or Six et al. (2001) have been used to isolate and chemically characterize carbon fractions. These fractionation techniques provide more insight into organic carbon cycling in the soil than the particle size separation method used in this experiment. A recent study by Sohi et al. (2001) compared several carbon fractionation methods and concluded that fractions obtained from two-stage density separations corresponded better with modeled pools than those from particle-size separations.

Organic carbon dynamics in the subsoil have not received much study, but may be characterized by slower rates of decomposition and influenced by current management practices (Gill et al., 1999). In the long-term rotation experiment, the TOC at the 20-60 cm depth was 17.1 t C ha^{-1} greater than in the pasture rotation than the annual rotation. The organic carbon content of the surface 20 cm was not measured in this study, but using the rates of organic matter change and levels of organic matter found in 1990 in this experiment as reported by Díaz (1992) estimates of TOC are 35.8 t C ha^{-1} for the annual rotation and 51.0 t C ha^{-1} for the pasture rotation. The difference in TOC between the two treatments at 0-20 cm is 15.3 t C ha^{-1}. These estimates need to be verified with field measurements, but show that the organic carbon found below 20 cm may account for 53% of the difference in TOC between the pasture and annual rotations within the top 60 cm of the soil profile. Therefore, carbon dynamics in the subsoil are responsive to management practices and can contribute greatly to carbon sequestration in these soils.

The two experiments used in this study differed primarily in their duration. The biological tillage experiment was selected to examine changes in organic carbon on a relatively short time scale of 9 yr, whereas the long-term rotation experiment reflected the effects of 38 yr of management. The biological tillage experiment revealed no treatment differences in TOC, while there were significant differences found between rotation treatments in the long-term rotation experiment. Though the lack of significant effects in the biological tillage experiment may have been due to the presence of bermudagrass, these two experiments do illustrate the fact that changes in soil organic carbon occur slowly over a long period of time. There may have been treatment differences in the biological tillage experiment, but only of small magnitudes that were difficult to measure or analyze with the procedures used in this study. Due to factors such as soil spatial variability it is difficult to detect and measure small changes in soil organic carbon. Therefore, long-term experiments are valuable for studies of organic carbon dynamics under different management practices, and can be used to evaluate management practices or potential sinks for carbon sequestration.

The objective of this study was to determine the influence of forage crops on soil organic carbon. Incorporating pasture phases in an annual crop rotation was shown to increase soil organic carbon levels. Higher organic carbon in this rotation may have been due to greater carbon additions or a slower rate of organic matter decomposition with forages. Incorporating perennial forages in crop rotations is one of several possible management strategies to increase soil organic carbon (Paustian et al., 1997a; Janzen et al., 1998). Other practices include decreasing tillage and increasing the use of fertilizers or organic amendments. Combining several management strategies to promote carbon sequestration may have a synergistic effect on increasing soil organic carbon levels (Dalal and Chan, 2001). For example, introducing a reduced tillage system into the pasture rotation may lead to further increases in soil organic carbon. A no-till system during the arable phase of the rotation would likely decrease soil erosion and decrease the loss of organic carbon in the surface layers observed during this phase. The combined effects of merging other production practices with the incorporation of forage crops to increase soil organic carbon requires further study.

5.5 Conclusions

Seven year forage stands increased the coarse POC fraction at the 0-7.5 cm depth. No other changes to organic carbon levels were significant, which may have been due to the short duration of the experiment or the presence of a perennial grass weed.

A 38 yr old rotation study showed that a rotation of pasture and annual cropping had greater TOC and organic carbon in three size fractions than an annual crop rotation at 20-60 cm. This may have been due to additional carbon inputs or a reduction in soil erosion during the pasture phase. Differences in the MAOC, or stable carbon fraction, were 3.2 and 1.6 g C kg^{-1} soil for the 20-40 and 40-60 cm depths, respectively. The POC fractions were more sensitive to management practices than TOC. The results of this experiment indicate that the organic carbon levels in the subsoil may contribute significantly to the carbon sequestration in these soils.

6. GENERAL DISCUSSION

This study was conducted to investigate the role of forage crops in improving soil conditions in Uruguay. Three separate experiments were used to examine forage roots, forage improvements to soil physical properties, and forage additions to soil organic carbon, though each of these elements are interrelated. The growth of forage roots can influence soil structure by creating biopores and binding aggregates, and soil structure will in turn affect root growth due to the ease of penetration, or soil strength, and root access to water and nutrients. Soil structure impacts on soil organic carbon levels by protecting carbon held within soil aggregates and soil organic matter can have various influences on soil structure, such as decreasing bulk density or increasing available water capacity. Root growth will control soil organic carbon levels via carbon additions and soil organic matter can affect root growth through its effects on soil structure.

The root characterization of three forage species (Chapter 3) shows that tall fescue has a greater number of roots with much smaller diameters than alfalfa or chicory, at least in the upper soil profile. This would indicate that the tall fescue would form more biopores, but of a smaller pore diameter than the other two species. The formation of biopores by alfalfa would tend to decrease and be of smaller diameter with increasing depth in the soil profile, but those formed by chicory would have a fairly constant diameter with depth. The experiment examining the biological tillage of tall fescue, alfalfa, and chicory (Chapter 4) was limited by the effects of a weed invasion and only one field season of data. Few distinct treatment effects on soil structure or crop productivity were found, though the early improved sorghum growth in the chicory and alfalfa treatments may have resulted from the presence of larger biopores near the soil surface that were easily penetrated by sorghum roots.

Distribution of soil organic carbon is related to root biomass, as opposed to root number or thickness. Half of the root biomass of was located in the top 10, 20 or 30 cm of the soil profile for tall fescue, alfalfa and chicory, respectively, and root biomass decreased with depth (Chapter 3). Soil organic carbon levels would be expected to follow a similar decrease with depth of the soil profile, as root carbon additions decreased, though each of the forage species can have carbon inputs to a depth of 1 m. Soil organic carbon fractions were found to decrease with soil depth (Chapter 5) and incorporating forages in a crop rotation was found to significantly impact on soil organic carbon found from 20-60 cm. Because forages were seen to influence soil organic carbon levels deep in the soil in the long-term rotation experiment, it is likely that they may also have an effect on the long-term soil physical properties at this depth.

This investigation of the role of forages for soil improvement in Uruguay centers on the currently practiced mixed cropping system, which rotates 3-4 yr of annual grain crops with 3-4 yr of grazed pasture. However, none of the three experiments in this thesis directly incorporated the effects of grazing animals. Grazing was often simulated by periodic mowing and returning crop residues to the soil surface in these experiments. Adding animals into the system may impact on each of the studies.

Grazing can affect root growth and distribution as plants respond to defoliation and a loss of resources. A consistent response of root growth to grazing has not been found and response will vary with such factors as the extent and intensity of grazing, and the plant species (Crawford et al., 1998).

Animal traffic from grazing can affect soil physical properties through compaction forces from animal hooves. Studies have found the effects of animal compaction to be limited to the surface 15 cm or less of the soil, though changes at a lower depth are more likely in recently tilled soils (Franzluebbers et al., 2000a; Greenwood and McKenzie, 2001). Soil compaction under grazing can alter root growth and penetration of the pasture species as well as following grain crops in rotation. However, the effects of poor soil structure on forage root growth may be small compared to the effects of defoliation (Greenwood and McKenzie, 2001).

The influence of animal grazing on soil organic carbon pools and carbon sequestration will result from a change in carbon inputs, the spatial deposition of waste products, and the release of greenhouse gases from cattle. Any effects of grazing on root distribution will alter the distribution of carbon inputs in the soil profile. As well, carbon pools may very spatially with the deposition of animal waste. Franzluebbers et al. (2000a) found that soil organic carbon decreased with distance from shade or water sources and will vary spatially under grazing, though the effects of waste deposition were limited to the surface soil layers. In another study, Franzluebbers et al. (2000b) concluded that grazing pastures, as opposed to haying, increased the storage of soil organic carbon and nitrogen, as measured in the top 20 cm. When considering using pastures to sequester carbon, it is important to factor in the effects of the entire cropping system on greenhouse gases and accounting will have to be made for the contributions by grazing cattle to CH_4 emissions in order to obtain a net balance of carbon additions and emissions in this mixed cropping system (Janzen et al., 1998; Smith, 1999).

It is also important to consider the influence of specific forage species on the net balance of greenhouse gases when considering forages for carbon sequestration. For example, chicory and alfalfa may have different effects on the whole balance of greenhouse gases. As a legume, alfalfa has the ability to fix nitrogen with the association of *Rhizobium*. This will increase nitrogen levels present in the soil and may increase fluxes of N_2O. However, including legumes can improve soil fertility without the use of additional fertilizers and, in a mixed pasture, may increase non-legume plant growth thereby increasing carbon inputs to the soil. This emphasizes the fact that a whole system greenhouse gas balance must be taken into account in order to accurately account for carbon sequestration.

The inclusion of forage crops in rotation was found to increase total soil organic carbon by 17.1 t C ha^{-1} at 20-60 cm after 38 yr (Chapter 5). With the estimates of Díaz (1992) for the 0-20 cm layer, the difference in organic carbon in the top 60 cm with the inclusion of forages would be 32.4 t C ha^{-1}. This indicates that over the 38 yr of the long-term rotation study an average of 0.85 t C ha^{-1} was sequestered annually. Annual estimates of carbon sequestration potential will be important if using agricultural soils to mitigate carbon emissions becomes internationally recognized and accepted. The annual increases in organic carbon may decrease with time as the soil reaches a new, higher organic matter equilibrium after a change in management practice.

The amount of land under pasture in some areas of South America is decreasing in favour of no-till annual crop production (Studdert et al., 1997; Díaz-Zorita et al., 2002). It is believed that no-till production can provide the same soil conservation benefits as including forages in crops rotations. Forage roots were observed to penetrate well up to 1 m in these soils and would be expected to influence soil properties up to this depth. The results from this thesis indicate that forage crops can significantly increase organic carbon levels at depth, though their effect on soil physical properties requires further study. The effects of no-till production on soil structure were not examined in this study. However, the improvements with no-till would be expected to be limited to the surface soil and not extend below the tilled layer. Therefore, forage crops may have a valuable role improving soil at depth in the profile, for example sequestering carbon below 20 cm. Further study can be made comparing the effectiveness of forage rotations and no-till practices to ameliorate soil structure and sequester carbon. Also, combining the two practices may produce synergistic effects in improving the soil.

Soil improvement in this study was assessed on the basis of changes to soil physical properties or additions of soil organic carbon. However, the use of forage crops may have positive effects on soil factors other than structure or organic matter. Soil quality has been defined as "the capacity of a specific 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). Indicators of soil quality are composed of biological, chemical, and physical properties including such factors as microbial communities, earthworms, nutrient concentrations, and salinity, as well as bulk density or aggregate stability (Karlen et al., 2001). Including forages in cropping systems may have positive benefits for other parameters of soil quality and further improve soil conditions. For example, nutrient content was not evaluated in this thesis, but the benefits of incorporating pasture legumes as a means to biologically fix nitrogen and decrease fertilizer inputs is widely recognized

(Entz et al., 2002). There are several mechanisms through which incorporating forage crops in the mixed cropping systems in Uruguay may improve the soil.

7. CONCLUSIONS AND RECOMMENDATIONS

The following points summarize some of the conclusions and recommendations resulting from the work of this thesis.

- The capacity of forages to perform biological tillage should be reassessed under weed-free conditions.
- Long-term cropping studies are valuable tools for assessing cropping system impacts on soil organic carbon.
- Including forages in crop rotations is an effective management practice to sequester carbon at depth.
- Soil organic carbon content of subsoil layers can have a significant contribution towards carbon sequestration.
- Future studies of pastures in cropping systems should look at interactions with animal grazing.
- Conducting thesis research overseas is an invaluable opportunity to learn about agriculture in other parts of the world.

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APPENDICES

Appendix A. Historical averages (1965-2000) for mean monthly temperatures and precipitation for the INIA La Estanzuela research station.

Month	Temperature (°C)		Precipitation
	Minimum	Maximum	(mm)
January	17.5	28.9	95.8
February	16.9	27.7	112.7
March	15.5	25.8	124.6
April	12.3	21.9	84.8
May	9.4	18.5	89.2
June	6.7	15.1	71.2
July	6.3	14.7	73.2
August	7.0	16.5	74.2
September	8.3	18.3	81.9
October	10.9	21.1	106.2
November	13.3	24.1	111.6
December	15.9	27.6	101.3

Appendix B. ANOVA model and tables for the statistical analyses in the biological tillage and long-term rotation experiments.

Model statement for a randomized complete block design.

$$y_{ij} = \mu + b_i + t_j + e_{ij}$$

where: y_{ij} = the measured variable for the i^{th} block in the j^{th} treatment
μ = the population mean of the measured variable
b_i = the effect of the i^{th} block
t_j = the effect of the j^{th} treatment
e_{ij} = the error effect of the i^{th} block in the j^{th} treatment

Biological Tillage Experiment (incomplete blocks)

- blocks are the field blocks, i = 6
- treatments are the forage species and annual rotation, j = 4

Source	df	Expected Mean Square	F value
Block	5	var (Error) + 2 var (Block)	MS (Block) / MS (Error)
Treatment	3	var (Error) + Q (Treatment)	MS (Treatment) / MS (Error)
Error	5	var (Error)	
Total	13		

Long-Term Rotation

- blocks are the sampling location, i = 3
- treatments are the plots, j = 6

Source	df	Expected Mean Square	F value
Block	2	var (Error) + 6 var (Block)	MS (Block) / MS (Error)
Treatment	5	var (Error) + Q (Treatment)	MS (Treatment) / MS (Error)
Error	10	var (Error)	
Total	17		

Appendix C. Crop rotation history since 1984 for the annual and pasture rotation treatments of long-term rotation experiment. The crop symbols are as follows: B=barley; Sun=sunflower; Sor=sorghum; W=wheat; P=pasture.

Year	Annual rotation			Pasture rotation		
	plot 5	plot 9	plot 18	plot 6	plot 8	plot 20
1984	B,Sun	Sor	W	B,Sun	Sor	P
1985	W	B,Sun	Sor	W	B,Sun	Sor
1986	Sor	W	B,Sun	P	W	B,Sun
1987	B,Sun	Sor	W	P	P	W
1988	W	B,Sun	Sor	P	P	P
1989	Sor	W	B,Sun	Sor	P	P
1990	B,Sun	Sor	W	B,Sun	Sor	P
1991	W	B,Sun	Sor	W	B,Sun	Sor
1992	Sor	W	B,Sun	P	W	B,Sun
1993	B,Sun	Sor	W	P	P	W
1994	W	B,Sun	Sor	P	P	P
1995	Sor	W	B,Sun	Sor	P	P
1996	B,Sun	Sor	W	B,Sun	Sor	P
1997	W	B,Sun	Sor	W	B,Sun	Sor
1998	Sor	W	B,Sun	P	W	B,Sun
1999	B,Sun	Sor	W	P	P	W
2000	W	B,Sun	Sor	P	P	P
2001	Sor	W	B,Sun	Sor	P	P
at time of sampling	no crop	W	Sun	no crop	P	P