EFFECTS OF AGRICULTURAL MANAGEMENT ON SOIL CARBON AND pH IN THE DOUGLAS DALY REGION OF THE NORTHERN TERRITORY

S. L. Bithell, P. Shotton and M. N. Hearnden

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Contact:

Northern Territory Government
Department of Primary Industry and Fisheries
GPO Box 3000
Darwin NT 0801
www.nt.gov.au/d

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SUMMARY

The objective of this report was to provide information on the effects of agricultural practices on soil pH and soil carbon (C) from three long-term agricultural trials in the Douglas Daly region of the Northern Territory (NT). In addition, the study sought to determine whether the soil C and pH measurements used in these trials were suitable for use as agricultural soil quality indicators for agricultural land in the NT.

The three trials studied the effects of tropical pasture species and mixtures on beef production (the Pasture Species Evaluation under Grazing Trial, 1973-2011); tillage practices for wet season arable cropping (the Rotation of Tropical Grains under Different Tillage Methods trial, 1983-2000); and mixed cropping rotations with differing ley pasture species and grazing intensities (the Ley Farming Systems Project trial, 1994-2000).

Most of the soil C measurements in this report were by a C oxidation method and are referred to as 'oxidisable C'. The tillage method trial showed that oxidisable C concentrations were higher under no-tillage management compared with conventional tillage. The supplementary application of urea (70 and 140 kg/ha) in this trial was also associated with lower oxidisable C. The mixed cropping rotation trial showed that the continual cropping of sorghum for successive seasons lowered oxidisable C. In contrast, one Cavalcade-based ley rotation showed increasing oxidisable C concentrations over the study period. However, both the pasture species trial and the mixed cropping rotation trial showed large annual fluxes in soil oxidisable C concentrations with most treatments having neither sustained incremental increases nor decreases.

In both the tillage method and mixed cropping rotation trials, there was evidence of significant soil acidification, but not in the pasture species trial. The soil pH results from separate studies made at these sites also indicated that acidification had occurred. Supplementary urea application (70 and 140 kg/ha) increased soil acidification in the tillage practices trial.

Key practices and factors that affected both soil pH and soil C were nitrogenous fertilisers, soil type, sampling depth, measurement methods, the type of agricultural system and seasonal variability.

The following recommendations are suggested for the effective use of soil C to monitor soil quality in agricultural soils in the NT:

1. Evaluate the use of more sensitive soil C measures than the modified Walkley Black oxidation method, in conjunction with a method to measure the total amount of soil C.
2. Sample areas with documented declines or increases in soil C, such as the trials reported here, to understand how these concentrations may change with time.
3. Determine the effect of nitrogenous fertilisers on soil C.
4. Only base conclusions at a single site on soil C values from multiple time-points.
5. Identity the most environmentally stable periods for sample collection due to large seasonal effects on soil C values.

The following recommendations are suggested for the effective use of soil pH to monitor soil quality in agricultural soils in the NT:

1. Improve the understanding of temporal variability in pH values.
2. Only base conclusions at a single site on soil pH values from multiple time-points.
3. Undertake studies to establish if the calcium chloride pH method is more sensitive and also more appropriate than a water-based pH method for agricultural soil quality monitoring in the NT.

4. Resample areas with documented historical agricultural acidification to determine if pH in these areas correct with time.
5. Determine the relative effects of crops, ley pastures and fertilisers on acidification.
6. Determine if acidification is occurring in association with continuous cropping and ley pasture rotations on commercial farms. If acidification problems are identified, methods to mitigate the effects of acidification and prevent future acidification need to be identified for land managers.
7. Study the buffering capacity of common agricultural soils in the NT to determine the risk of acidification.
8. Identify environmental and cost-effective pH management strategies for use in mixed cropping and continuous cropping rotations.

The following general recommendations are suggested for monitoring soil quality in agricultural soils in the NT:

1. Develop a database of results from trials and surveys on agricultural land so that useful information can be gained from existing analyses.
2. Develop a set of agricultural soil quality indicators, including soil pH and soil C, that include recommended analysis methods and sampling protocols.
3. Develop a soil quality monitoring program based around demonstrating the value of monitoring and the use of designated monitoring sites on government and prominent private farms.

1 INTRODUCTION

Maintaining agricultural soil quality is important for sustaining production levels and protecting soil resources for future use. There is limited available information on the effects of agricultural management on soil quality in the NT, although the soils used for agriculture are considered to be at some risk from erosion, loss of C, crusting, acidification and nutrient loss (Smith and Hill 2011). Early studies indicated that some NT soils were sensitive to arable cropping practices; for example, in the 1960s, five years of cropping on a Blain soil in Katherine was reported to have contributed to soil erosion at the site and a rapid loss of soil nitrogen (N) from the surface layers(Arndt et al. 1963). Another soil type (Florina) was found to be unsuitable for arable cropping due to poor production and high levels of erosion (Arndt et al. 1963). Following that time, no-tillage and stubble retention techniques were developed to protect the soil surface and improve production on Blain soils (McCown et al. 1985). However, there is little information on the long-term effects of agricultural practices on soil quality in the NT.

Long-term studies may be used to monitor changes in soil quality in relation to management or environmental factors (Rasmussen et al. 1998). At the Douglas Daly Research Farm (DDRF), three multi-year studies evaluated the effects of (1) tropical pasture species and mixtures on beef production (the Pasture Species Evaluation under Grazing Trial, 1973-2011); (2) tillage practices on wet season arable cropping (the Rotation of Tropical Grains Under Different Tillage Methods trial, 1983-2000); and (3) mixed cropping rotations on differing ley pasture species and grazing intensities (Ley Farming Systems Project trial, 1994-2000) (Plate 1). As part of these studies, soil samples were regularly collected but results were not evaluated, with the exception of the tillage trial where some early data was summarised (Thiagalingam et al. 1996). No analyses of soil quality have been previously reported from the other two trials. This report sought to review data from the three multi-year studies and evaluate the effects of agricultural practices on changes in soil C concentrations and pH values. This information will be of specific use to NT and northern Australia-based agronomists and soil and environmental scientists, especially those interested in developing soil quality programs for land under agricultural management.

An additional objective of the work was to provide information on the suitability of soil C and pH measurements as agricultural soil quality indicators in the NT. Suites of soil quality indicators have been developed in Australia and overseas for use by farmers and consultants to allow ongoing soil quality monitoring (Southorn and Cattle 2000; Schwenke et al. 2003; Kelly et al. 2009). These indicators have usually been identified from prior studies in the target region and have then been developed and evaluated with sensitivity, cost and ease of interpretation being of central importance (Pankhurst et al. 1995; Freebairn and King 2003; Erkossa et al. 2007; De Bona et al. 2008; Golchin and Asgari 2008; Sharma et al. 2008; Zagal et al. 2009). The results from the multi-year studies at DDRF provide information on the utility of the soil C and pH methods used, which will be relevant to the development of a set of agricultural soil quality indicators for use in the NT.

1.1 IMPORTANCE OF SOIL CARBON

Soil C, also described as soil organic C, is the C resident in soil. Soil C is present in a number of forms, ranging from highly labile fractions through to charcoal and carbonates, which are relatively inert (Rayment and Higginson 1992; Chan et al. 2001). Soil C is an important component of soil organic matter and includes minerals, nutrients and decaying plant and animal remains (Dalal and Carter 2000; Weil and Magdoff 2004). Soil C values are sometimes reported as representing soil organic matter; however, they are not equivalent. A number of conversion factors have been used to estimate the amount of organic matter from soil C values. For example, some conversions use the assumption that soil organic matter contains 58% C; however, this value is only accurate for some soils or fractions of soil C (Pribyl 2010).

Plate 1. Aerial photograph showing the paddock layouts of the Ley Farming Systems Trial (top), and the Pasture Species Evaluation under Grazing Trial (centre right). The Rotation of Tropical Grains Under Different Tillage Methods Trial is located away to the right of this image.

Soil organic matter is particularly important for maintaining physical, chemical and biological fertility of tropical soils with low clay contents or low activity clays, such as kaolinite (Dalal and Carter 2000). The link between soil C and soil organic matter is important as soil organic matter has a number of important roles, including as a source of plant nutrients (such as N, P and S), a major C and energy source for microorganisms, for contributions to cation exchange capacity, as a sink for nutrients that may be lost through leaching, for contributions to buffering capacity, for promoting soil aggregation and water infiltration and as a sink for atmospheric C (Dalal and Carter 2000; Weil and Magdoff 2004).

There is currently a large amount of interest in soil C concentrations due to programs examining C sequestration. This has led to recent work, including a reappraisal of the effects of agricultural practices on soil C. Key areas of focus are the effects of cultivation (Luo et al. 2010) and the effects of clearing native vegetation, with replacement by forestry, pastoralism or arable farming (Brye and Slaton 2003; Law and Garnett 2009).

Soil C concentrations are known to be relatively low in the highly weathered soils of the NT with average total combustible C in the surface sample zone (10 cm) close to a concentration of 1% (Hancock et al. 2010).

The oxidation rate of C in the tropics has been shown to be four times that of in a temperate system (Jenkinson and Ayanaba 1977). Because of this, it is important to understand the effects of land management practices on soil C concentrations in tropical regions (Lal 1985).

Soil C is an important soil quality indicator in monitoring systems under agricultural management in Australia (Bell et al. 1999; Dalal et al. 2003; Weil and Magdoff 2004).

1.2 SOIL CARBON MEASUREMENT

The measurement of soil C and soil organic matter, in particular, is a complex area with many new methods being developed to measure particular C fractions or components of organic matter (Shang and Tiessen 1998; Chatterjee et al. 2009; Hockaday et al. 2009). For the purposes of this report, we focus on describing the methods and terminology relevant to the three DDRF trials.

The Heanes modified Walkley Black (W-B) method was used in all the three DDRF trials to measure soil organic C concentrations (Heanes 1984; Rayment and Higginson 1992). This is a particular version of one of the two W-B methods (Walkley and Black 1934; Walkley 1947).

Various versions of the W-B method have been used in Australia to measure soil organic C concentrations (Heanes 1984; Wang et al. 1996; Skjemstad et al. 2000; Chan et al. 2001; Mendham et al. 2002; O'Brien et al. 2003). The first W-B method was based on the wet oxidation of organic C, whereby concentrated sulphuric acid is added to the soil, wetted with a dichromate solution; the acid-based reaction oxidises organic matter (Walkley and Black 1934). Here we describe this first method as the 'non-modified W-B method'. The method was further developed by the inclusion of additional heating to improve the extent of oxidation (Walkley 1947). This second method is commonly referred to as the 'modified W-B method' (Chatterjee et al. 2009; Meersmans et al. 2009). Both methods are unable to estimate total soil C contents due to their inability to oxidise inert organic C compounds, such as charcoal and carbonates. Therefore, oxidation correction factors are widely used for particular soil types to estimate total C contents (De Vos et al. 2007; Chatterjee et al. 2009; Meersmans et al. 2009). In Australia, an additional development was the use of a block digester at 135 °C to improve the extent of oxidation as well as the use of an absorbance method calibrated against sucrose standards to measure concentration (Heanes 1984; Rayment and Higginson 1992). In contrast to the methods used in a number of other countries, there was no attempt to convert Heanes' modified W-B method values to total C values with oxidation correction factors (Rayment and Higginson 1992). We use the term 'modified W-B method' to describe this method. Most of the soil C analyses for the three DDRF trials used this method. The modified W-B methods have higher C recoveries than the non-modified W-B methods but there is also variation in the level of recoveries between laboratories due to differences in procedures (Jolivet et al. 1998; De Vos et al. 2007).

Another commonly used method to measure carbon is that based on high temperature combustion, which measures all C forms, including carbonates and charcoal (Rayment and Higginson 1992; Jolivet et al. 1998; Weil and Magdoff 2004). Results from this method are commonly referred to as 'total C' (Rayment and Higginson 1992; Chatterjee et al. 2009; Meersmans et al. 2009).

The oxidation correction factors used in either the modified or non-modified W-B methods are intended to provide equivalence with total C results. In this case, the results of 'W-B organic C' and 'total C' concentrations may be similar, or the same, for example as shown for the analysis of soil samples from New South Wales (Skjemstad et al. 2000). The methods used to measure soil C have a large effect on calculated values (Brye and Slaton 2003). Therefore, some caution is required when a correction factor is used with interpreting W-B soil C results and/or if modified methods have been used, especially for comparisons with combustible total C results. Results may be described as 'organic C' or 'total C' but depending on the methods used, the values can be the same or very similar. To avoid potential confusion, this report refers to the values from all W-B methods as 'oxidisable C' (ox. C) and from combustion methods as 'total C' values.

1.3 IMPORTANCE OF SOIL PH

Since the early 1990s, there has been concern over the soil condition and sustainability of tropical grasslands in Australia with salinity and soil acidification of particular concern (Williams and Chartres 1991). Later work identified that subsurface (>50 cm in depth) acidification was common in a number of Australian tropical agricultural systems, including arable cropping and horticulture, and the rates of acidification were higher than those for temperate systems (Moody and Aitken 1997). In that study the leaching of nitrates from fertilisers was identified as a major contributing factor to acidification. A recent review of agricultural soil condition in the NT identified organic matter accumulation and profile leaching of nitrate as important factors affecting soil acidification (Smith and Hill 2011). Because of the effects of acidification on land condition and productive capacity, soil pH is an important soil quality indicator. Because of the importance of soil pH and soil C, they are the two most common soil quality indicators included in monitoring and appraisal of soil quality (Weil and Magdoff 2004).

1.4 COMMON METHODS

This report cites results from the analyses of soil samples from three field trials. All soil samples prior to those collected from the Species trial in 2010 and 2011 were analysed by the Chemistry Section at the Berrimah Agricultural Research Centre, Department of Primary Industry and Fisheries (DPIF). In these cases, the same methods were used to measure soil pH and ox. C across the three trials. The methods of analysis of the 2010 and 2011 samples from the Species trial are described separately in Section 2.1.

For the determination of soil C, Heanes' modified W-B method was used (Heanes 1984; Rayment and Higginson 1992) with a 0.5 g sample for analysis. Briefly, C in samples is oxidised by dichromate sulphuric acid solution utilising the heat of solution of sulphuric acid, followed by an additional heating stage at 135 °C. The absorbance of green chromous ions was measured at 600 nm with a spectrophotometer and a comparison with a standard curve generated from sucrose samples was used to determine the percentage organic C on a dry weight basis.

The pH of samples was measured using a water-based method (pH H_2O) determined by extracting a sample of soil with water using 8 g of soil and 40 mL of water and measuring the pH with a pH meter (Rayment and Higginson 1992).

1.5 WEATHER AT DDRF

A Bureau of Meteorology (BOM) weather station has operated at the DDRF since 1968 (BOM station number 014901); it is situated approximately 1.6 km, 4.1 km and 1.6 km from the centre of the Species, Rotgut and Systems trials, respectively.

The long-term (1968-2011) average annual rainfall recorded at DDRF is 1183 mm, most of which occurs during the wet season, from November or December through to March (Anon 2011) (Figure 1.1). Based on long-term averages, during the period from November to March inclusive there are more than five days a month with rainfall greater than 1 mm. Average values for these respective months are 7.6, 11.0, 14.1, 13.8 and 11.3 days per month. On average, during the period from December to March inclusive, average values for these respective months are 5.5, 7.5, 7.5 and 6.0 days per month.

Monthly mean minimum air temperatures do not get lower than 12.5 °C and average ~23.7 °C, over the wet season. Monthly mean maximum air temperatures have a lower range than minimum temperatures, ranging from 31.1 °C in June through to 37.5 °C in October.

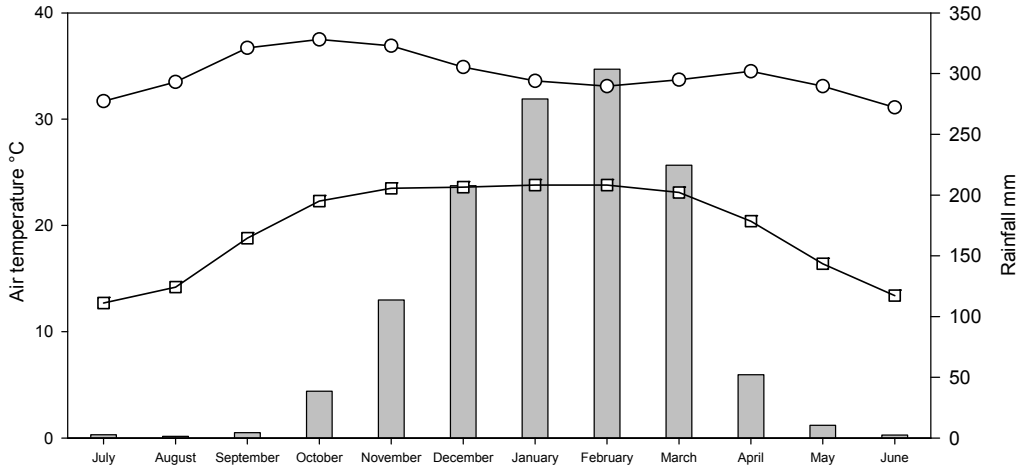

Figure 1.1. Long-term data (1968-2011) for mean maximum (○) and minimum (□) monthly air temperature (left y axis) and monthly average rainfall (vertical bars, right y axis)

2 SPECIES TRIAL

A long-term study of pasture species and mixtures and cattle grazing performance called the *'The Pasture Species Evaluation under Grazing Trial'* was established in 1968 at DDRF. This trial is still operating and is commonly referred to as the 'Species trial' (Shotton 2011).

The objectives of the 'Species trial' were to evaluate introduced tropical pasture species and mixtures under a continuous grazing regime on Blain soil at DDRF, determine their persistence, productivity and contribution to the weight gain performance of cattle and identify pasture management recommendations for livestock producers (Rann 1991-1994; Murti 1993; Zuill 1995, 1996 and 1997; Lemcke 2002, 2003 and 2004; Murti 2007; Shotton in prep). The trial is situated on what has been commonly referred to as a Blain soil. Recently, descriptions of common agricultural soils in the NT have been summarised (Hill et al. 2011) and this type of Blain is described generally as a Sandy Red Earth and has an Australian soil classification as a Deep Red Magnesic Kandosol (Hill et al. 2011). Two soil description pits were dug in the trial area in 1979 (NRETAS 2011). The location and soil descriptions from these are provided in Appendix 1.

The study was designed as a series of 19 non-replicated rectangular 4-hectare fields that are arranged side to side in a single row (Plate 1). Each field is 540 m long and 75 m wide; the total trial area is 1.4 km long. Table 2.1 presents field order, current pasture species treatments and details major changes made to pastures during the study period. Most fields were top-dressed with fertiliser each year in either November, December or January depending on seasonal conditions; typical rates were 50 kg/ha of single super and trace elements before 1998, then from 1998 the fertiliser was an NPKS mix of 0-16-0-20 at 50 kg/ha. Four fields had N fertiliser treatments (prilled urea, 46% N), for some periods: field 44 (December 2002, 80 kg/ha), field 45 (1997, 98, 99 and 2000 100/kg/ha), field 46 (1999, 2000, 2001 100 kg/ha, 2002 80 kg/ha), and field 532 50 kg/ha of urea in both December and March each year from 2003 to 2006 and in 2008). Fertiliser applications also occurred when new pastures or crops were sown in some fields. For example, there were a series of crop changes in field 43, such as silk sorghum and Maldonado sown in the 1995-96 season, which was fertilised with 50 kg/ha single super and trace elements at sowing. This was typical sowing fertiliser practice. From 1972, the stocking rate was two steers (approx. 0.8 animal equivalents (AE)) and two yearlings (0.5 AE)/4 ha. From 1979 the stocking rate was increased to 1.5 animals/ha (six per paddock). The stocking rate was reduced to one animal/ha in 1988 to 2000 with the market specifications becoming more aligned to the South-East Asian export market. From 2001, the stocking rate increased in order to better utilize available pasture resulting in a final stocking rate of 1.5 animals/ha (0.86 AE/ha). The exceptions to these stocking rate protocols were paddocks 39 and 49, which had a stocking rate of 2.5 animals/ha (1.49 and 1.41 AE/ha), in order to monitor the long-term effects of heavier stocking rates on the pasture. Paddock 39 was divided into two and grazing was rotated monthly to allow the leucaena *(Leucaena leucocephala)* to recover leaf on a regular basis. Steers were allotted to paddocks in June/July (post weaning) and remained in the grazing trial for 12 months until the following June. Further details on pasture treatments and management practices are presented in Shotton (Shotton in prep).

Table 2.1. Species trial treatments presented in order from north to south

Field code	Current pasture treatment	Major changes to pasture treatments
43	Signal grass *(Brachiaria decumbens)* sown in 2007.	Sabi sown pre-1988, Cavalcade (*Centrosema pascuorum)* over-sown in 1988 to create a mixed pasture. Silk sorghum and Maldonado (1996-1998), silk sorghum re-planted with Milgara blue pea (*Clitoria ternatea)* December 1998. Higane (*Paspalum atratum*) 1999-2003 Oolloo (*Centrosema brasilianum)*, 2003 to 2006. Forage sorghum planted in January 2006 followed by Signal grass sown in December 2007.
44	Pangola grass (*Digitaria eriatha*) planted in the 1970s. Pangola runners planted in ex. leucaena rows 2002.	Leucaena planted pre 1990. Leucaena removed 2002 and urea (80 kg/ha) applied for pangola establishment.
45	Pangola grass and Verano stylo *(Stylosanthes hamata)* sown in the 1970s. Leucaena 2001 and 2004.	Urea 100 kg/ha 1997, 1998, 1999, 2000. Leucaena planted (12.5 m rows) in half of field 2001 and in the second half in 2004.
46	Sabi grass *(Urochloa mosambicensis)* and Verano stylo *(Stylosanthes hamata)* sowed pre 1990.	No major pasture changes. Urea 100 kg/ha 1999, 2000, 2001 and 80 kg/ha 2002.
47	Jarra grass sown and established in 1995	No major changes.
48	Sabi grass *(Urochloa mosambicensis)* sown 1997, leucaena 1999 and 2004.	Blue grass *(Bothriochloa* spp*.)* and Wynn cassia sowed early 1980s. Kazungula *(Setaria sphaceolata)* sown 1997 but absent by 2004. Leucaena planted (10 m rows) in half of field 1999 and remainder 2004.
49	Buffel (*Cenchrus ciliaris* cv. s Gayndah, American) and Milgara. Blue Pea (*Clitoria ternatea)* oversown buffel 1990 and 2008.	Indian blue grass *(Bothriochloa pertusa)* established pre 1989. Glenn joint vetch *(Aeschynomene americana)* over sown in buffel but did not establish.
50	Buffel grass *(*cv. *Gayndah* sown mid-1980s and five different pasture legumes Wynn cassia, Verano stylo, Oolloo, Maldonado (*Macroptilium gracile*) and Milgara Blue Pea planted as separate pastures in 2000.	The paddock was originally planted with buffel and Cavalcade in the mid-1980s. Replicated pasture species trial run in this field from year 2000.
51	Strickland Finger grass *(Digitaria swynnertonii)* over-sown in 1998 and three lines of *Chamaecrista rotundifolia.*	Thatch grass (*Hyparrhenia rufa*) and Verano stylo planted pre-1990, the *Hyparrhenia* did not establish. Three lines of *Chamaecrista rotundifolia* and Wynn cassia planted 1996.
52	Arnhem grass *(Digitaria swynnertonii)* and Oolloo established in 1997	Planted with gamba grass *(Andropogon gayanus*) pre-1987, and over-sown with Milgara blue pea 1991. Gamba ploughed out 1997
531	Buffel (cv Gayndah) and Sabi grass estab. pre-1990, Wynn cassia self-spread to field since 1999	1992 half the field sown with *Calliandra*, the *Calliandra* was absent by 1994.
532	Buffel (cv Gayndah) and Sabi grass estab. pre-1990, Wynn cassia self-spread to paddock since 2000	1992 quarter of field planted leucaena (8 m rows); leucaena did not sustain early heavy grazing, grazed out by 1994. Urea 100 kg/ha 2003-06 and 2008.
533	Buffel, sabi grass and Wynn cassia sown pre-1990	No major changes.
534	Buffel, sabi grass and Wynn cassia sown pre-1990, leucaena 1993 and 2004.	Early 1990s the field planted with leucaena (8 m rows); in 2000 every second row was removed.

The trial also contains five more fields than those presented in Table 2.1. They are fields 39, 40, 41 and 42 which are situated to the north of field 43. To the south of field 534 is field 535. Some of these fields were relatively recently established or had treatment changes relatively recently. In particular, field 39 was divided in two fields in 2006, field 40 had a change in pasture species in 2004, fields 41 and 42 were part of a cropping rotation research trial prior to 2003, and field 535 had ~ 25 species of fodder trees established in one end in 1996 and was over-sown with a different grass species in 2002. These fields also did not have regular soil sampling so were excluded from analysis and contemporary sampling in 2010 and 2011.

Overview of trial and soil quality report focus

Where possible, factors identified as affecting soil pH or soil C concentrations in pastures from other Australian or international studies were investigated (Williams and Chartres 1991; Moody and Aitken 1997; Dalal and Carter 2000; Fenton and Helyar 2007). The trial provided an opportunity to investigate the effects of pasture species, pure grass to mixed grass-legume pastures, and mixed pastures or pure grasses to a tree legumes (leucaena) for effects on soil pH and ox. C concentrations. Historic sampling had been based on three soil core samples per field; the variability of this method and the effects of slightly more intensive sampling were investigated. An evaluation of seasonal variation of soil pH and ox. C concentrations was also made. A comparison was also made of soil pH and ox. C from an uncleared area of similar soil type to the fields in the trial. Finally, linear relationships were used to investigate evidence for increases or decreases in soil pH and ox. C concentrations over the period of sampling in the fields.

2.1 METHODS

The land on which the trial is conducted was cleared between 1962 and 1963. In the period following clearing to the establishment of the trial, the area had mostly sabi or pangola pasture but some annual cropping of grain sorghum and maize also occurred. Some areas were also managed as native annual pastures that included the species *Digitaria ciliaris*, *Brachiaria miliiformis, Erodium crinitum, Dactyloctenium radulans, Cynodon dactylon, Sorghum* spp. and *Hereropogon* spp. GPS corner points of the study area are S 13^0 50.236, E $131^0$11.938; S 13^0 50.258, E $131^0$12.266; S 13^0 50.981, E $131^0$11.905; S 13^0 51.000, E $131^0$12.214.

Historical soil sampling

The majority of soil sampling that took place from 1995 to 2002 was based on the collection of three cores (40 mm, diameter (D)). For samples collected from 1995 to 1998, a single transect (lengthwise) from corner to corner was used (D. Reilly pers. comm.). Along this transect, three quadrats (0.5 m^2) were placed for soil sampling. Pasture and weed species composition was assessed in the quadrats and herbage samples were collected. Then a single soil core was collected. During the 1995-98 period, some soil samples (1995, 1996 and 1998) from each quadrat were kept separately and labelled in sequential order (1, 2 and 3) to identify the within-field location (1 near the gate end, 2 near the middle, 3 near the far end) of samples (Table 2.2). At all other sample dates the three cores were bulked into a single sample for analysis.

For the period from 1999 to 2002, quadrats were placed along a V-shaped transect. Along this transect three quadrats (0.5 m^2) were placed. The first two placements were in the first arm of the V transect and were made approximately 50 m from each end of each field. The third quadrat was placed in the middle of the second transect arm, which was near the middle of the length of the field.

The time of sampling each year varied, but in general, sampling followed a strategy of sampling during the early to mid-dry season (March to June) and at the end of the dry or early wet each year (September to December). There were exceptions to this pattern with three samples (March, July and September) collected in 1995 and in some years (1994, 2000 and 2001) only a single sample was analysed. The depth of

sampling was generally 0-15 cm, but on five occasions both 0-15 cm and 15-30 cm samples were collected and analysed.

Table 2.2. Record of soil sampling dates, depths and sampling methods from past studies

Date	Depths (cm)	Sampling method	References
June 1994	0-15	unknown	(Rann 1991-1994)
Feb. 1995	0-15	3 bulked cores	(Zuill 1995, 1996 and 1997)
July 1995	0-15	3 bulked cores	
Sept. 1995	0-15	Separate analysis of 3 cores	
April 1996	0-15	Separate analysis of 3 cores	(Zuill 1995, 1996 and 1997)
May 1997	0-15	3 bulked cores	(Zuill 1995, 1996 and 1997)
Dec. 1997	0-15	3 bulked cores	
May 1998	0-15	Separate analysis of 3 cores	(Pers. comm. D. Reilly)
Dec. 1998	0-15	Separate analysis of 3 cores	(Pers. comm. D. Reilly)
	15-30	Separate analysis of 3 cores	
May 1999	0-15	3 bulked cores	(Lemcke 2000 and 2001)
	15-30	3 bulked cores	
Dec 1999	0-15	3 bulked cores	(Lemcke 2000 and 2001)
	15-30	3 bulked cores	
May 2000	0-15	3 bulked cores	(Lemcke 2000 and 2001)
	15-30	3 bulked cores	
June 2001	0-15	3 bulked cores	(Lemcke 2002, 2003 and 2004)
	15-30	3 bulked cores	
Dec 2001	0-15	3 bulked cores	(Lemcke 2002, 2003 and 2004)
	15-30	3 bulked cores	
April 2002	0-15	3 bulked cores	(Lemcke 2002, 2003 and 2004)
	15-30	3 bulked cores	

2010 and 2011 soil sample collection methods

For 2010 and 2011 particular fields were sampled. These fields were selected on the basis that major changes in pasture treatments had not been recently made. Table 2.3 details the sampled fields and provides a summary of the pasture type and estimated composition of legumes and grasses. Samples were collected on 20 October 2010 from the 0-15 cm and a 15-30 cm zones using two methods in each sample paddock. Firstly, the three core method (transect method for samples) described in the previous section was used. In addition, a second sampling method was used based on cores collected from 10 sites using a standard soil sampling W collection pattern (McLaren and Cameron 1984), with 5 arms (VV\) to the pattern. For this method 10 cores were collected with two cores randomly taken when walking along each arm of the VV\ pattern. Fields with leucaena (45, 48 and 534) also had 10 cores taken using the VV\ pattern, with samples collected ~15 cm from the centre of the tree row, in addition to the separate sampling of the pasture in each field.

At each coring site, plant residues were brushed away from the soil surface before coring. Following collection, the samples were dried at 60 °C for 48 h within 24 h of collection; samples were then sieved (2 mm) and plant material was removed prior to sending 350 g soil subsamples to CSBP, Pibra Lake, Western Australia, for analysis.

In 2011 only the 10 site method was used and no separate leucaena samples were collected.

Uncleared bush area sampling: 2010 and 2011

Soil samples from an uncleared area of bush were collected approximately 0.5 km from paddock 535. Predominant species present included *Hiptis suaveolens*, ironwood (*Acacia estrophiolata*), *Eucalyptus* spp., sandpaper fig (*Ficus opposite*) and *Pandanus* spp. No grass species were present at this site.

Samples were collected from three separate areas (Bush A, Bush B and Bush C). At the bush site, each area was ~ 150 m apart and each collection area was about 50 m in diameter. From within each of the three areas, four cores were taken. The locations were identified with a GPS (5 m accuracy) in 2010. This method was used to return to each sample area in 2011. The central area of the location was S 13^0 51.270, E $131^0$11.680. A soil description pit was dug ~650 m from the bush sample area in 2007 (NRETAS 2011). The location and soil descriptions from this are provided in Appendix 1.

Table 2.3. Record of the 12 fields sampled in 2010 and 2011 with the respective percentage composition (mix %) of grass and legume, broad-leaf legume and tree legume species in terms of estimated dry matter composition, the last year of major pasture treatment changes is also indicated

Field code	Predominant pasture species	% mix	Major changes	2010 and 2011
39	Buffel / leucaena		2003	not sampled
40	Buffel		2004	not sampled
41	Tully		2003	not sampled
42	Jarra grass		2004	not sampled
43	Signal		2007	not sampled
44	Pangola	100	2002	1
45	Pangola + leucaena	80:20	2004	2
46	Sabi	100	pre 1990	3
47	Jarra + Crotalaria*	95:5	1995	4
48	Sabi + Wynn + leucaena	85:15	1999	5
49	Buffel + Blue pea	80:20	1990	6
50	5 legume species + buffel		2000	not sampled
51	Strickland + Wynn	80:20	1998	7
52	Arnhem + Oolloo	98:2	2002	8
531	Buffel + Wynn*	95:5	1992	9
532	Buffel + Wynn*	90:10	1992	10
533	Buffel + Wynn	85:15	1992	11
534	Buffel + leucaena	75:25	2004	12
535			2002	not sampled

* Self-established

Analysis of 2010 and 2011 soil samples

From each sample collected in 2010 and 2011 a 200 g subsample was sent for analysis at the CSBP Soil and Plant Analysis Laboratory, Bibra Lake, West Australia.

A non-modified Walkley Black (W-B) method was used to determine soil ox. C content (Walkley and Black 1934) on 0.50 ± 0.05 g samples. Chromic ions proportional to oxidized soil C were measured colorimetrically at 600 nm on a Multiscan. Total C, including both inorganic and organic forms, was also measured. Sample values were determined on a LECO combustion analyser. The soil samples (0.20 ± 0.02 g) were loaded into a sealed glass combustion tube (at 950 ˚C) and flushed with oxygen. Generated gases were collected and measured on both an infrared detector and a thermal conductivity cell to measure total C.

The soil pH was determined at CSBP using both water and calcium methods, as follows: soil was mixed with deionised water in a soil: solution ratio of 1:5 for 1 hour. The pH H_2O and electrical conductivity of the extract was subsequently measured using a combination pH electrode. After water pH and EC were measured, a

calcium chloride solution was added to the soil solution and after thorough mixing the calcium chloride, its pH (pH $CaCl_2$) was determined (Rayment and Higginson 1992).

Data analysis

Analysis was based on data summaries with comparisons of mean values from plots over time between species pasture treatments. Although fields were sampled on a seasonal basis, repeated measures analysis (ANOVA) was not considered in these comparisons due to the absence of proper replication (methods varied with time and the fashion in which depth profiles were sampled) and the relatively low number of treatments. Therefore, data from different seasons from the same fields was treated as being independent (although it is unlikely to have been wholly independent). For fields that had soil analyses of separate samples (typically from three positions in a field) from a single sample month, each month was analysed separately for the effect of sample position and field (species) with ANOVA. Paired t-tests were used for comparisons of analyses from fields where values from two time-points were being compared (e.g., pH values from each of the 12 fields sampled in 2010 and 2011). A Wilcoxon Rank Sum test was used to compare paired pH and ox. C values from seven fields for a series of consecutive seasonal samples. Independent sample t-tests were used to compare data with no pairing structure. For example, for values from three bush sites to three buffel fields, pooled variances were used for the calculation of P-values for the two sample t-tests. Bonferroni's adjusted probabilities were used for the calculation of P-values for both paired and two-sample t-tests. Linear regression of the cumulative day count for each sample occasion for selected a field with long-term results series was used to examine the data for significant trends over time where linear, with the data excluded (2010-11 and December 2001-2010-11) from some analyses in order to identify the influence of data from particular years. Analyses were carried out with Systat.

2.2 RESULTS

2.2.1 Weather during the sample period

The long-term average rainfall for the four months of peak rainfall (1067 mm) was close to the average rainfall (1183.6 mm) for the period of the trial discussed in this report (1993-2011) (Table 2.4). However, variation around this average was substantial, with three wet seasons having 200 mm of rain less than the long-term average; the driest was the 2008-09 season. In contrast, seven wet seasons were more than 200 mm wetter than the long-term average value. The most rain in a wet season occurred over the course of the 2010-2011 wet season (1805 mm). This was more than double the driest wet season (2008-09) with 742 mm. The total rainfall over the 12 months of each season from July to June followed similar patterns with the amount of rainfall outside the peak wet season months contributing to about 10% of the average seasonal total. The 2005-06 season had the most rainfall (19.4% of the total) outside the peak wet season months. Both average wet months and total seasonal rainfall had proportionally high coefficients of variation.

Table 2.4. Rainfall (mm) recorded at DDRF for the Species study for which soil results are available (1993-2011) for the long-term average wettest months (1 December to 30 April, wet season), annual seasonal rainfall (1 July to 30 June) and the December to April wet season rainfall as a percentage of annual seasonal rain, including mean, standard deviation and coefficients of variation (CV) for the seasons in the study period

	Dec.-Apr. (wet)	June-July	% wet of annual
Average for 1968-2011	1067.4	1182.7	90.3
1993-94	1118.7	1130.5	99.0
1994-95	782.9	849.6	92.1
1995-96	965.1	1096.7	88.0
1996-97	1064.2	1269.2	83.8
1997-98	1595.6	1695.8	94.1
1998-99	1472.3	1590.6	92.6
1999-2000	1289.5	1449.4	89.0
2000-01	1080.4	1192.8	90.6
2001-02	953.0	1157.8	82.3
2002-03	829.3	930.7	89.1
2003-04	1426.8	1501.4	95.0
2004-05	887.8	999.8	88.8
2005-06	1493.8	1854	80.6
2006-07	1051.8	1117.4	94.1
2007-08	1760.6	1937.8	90.9
2008-09	742.6	846.6	87.7
2009-10	985.4	1115.6	88.3
2010-11	1805.0	2031.6	88.8
Mean	1183.6	1320.4	89.7
Std. dev.	78.7	87.6	1.1
CV	333.7	371.8	4.6

2.2.2 Variability and sampling effort

Selected comparisons of results from specific sets of samples were made in order to identify what variation in pH and ox. C values were at the site and what effects sampling intensity had on values for these parameters.

Variation within fields: historical samples

For four sample dates a separate analysis comparing results from the three individual cores in each field was made, using the factors sample position (1 near the gate end, 2 near the middle, 3 near the non-gate end) and field for each of the five sample sets shown in Tables 2.5 and 2.6. For both pH H_2O and ox. C, the sample position effect did not differ significantly, which indicated there was no consistent variation (at the 5% level) or a gradient in pH or ox. C values across all fields.

Table 2.5. pH H_2O values for four samples dates for which three separate cores were analysed, P values are for the factors field (as listed for each year) and sample position (1, 2, and 3), standard error of the mean (SEM) is also presented, the tHSD value is provided for significant effects. Note: Different sets of fields were sampled with the three separate core method in the four years.

Time	September 1995	April 1996	May 1998	Dec. 1998	Dec. 1998
Depth (cm)	**0-15**	**0-15**	**0-15**	**0-15**	**15-30**
Field code					
43	-	6.20	-	6.10 a	5.43 a
44	6.57	6.50	6.10	6.77 b	6.67 b
45	6.33	6.30	5.87	6.47 ab	6.76 b
46	6.73	6.6	6.13	6.63 ab	6.60 b
47	6.77	6.47	-	6.93 b	6.47 b
48	-	-	6.0	6.83 b	6.63 b
49	6.50	6.23	-	6.73 ab	6.60 b
50	-	-	-	-	-
51	-	6.07	-	6.50 ab	6.70 b
52	-	6.27	-	6.40 ab	6.33 b
531	7.03	6.40	6.13	6.57 ab	6.37 b
532	6.80	6.37	5.97	6.60 ab	6.73 b
533	6.80	6.43	6.27	6.83 b	6.83 b
534	6.77	6.50	6.17	6.60 ab	6.50 b
N	27	36	24	39	39
Field P	> 0.05	> 0.05	> 0.05	0.0208	< 0.0001
Sample position-P	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Grand mean*	6.70	6.36	6.10	6.61	6.51
SEM*	0.054	0.152	0.038	0.046	0.064
tHSD	-	-	-	0.668	0.637

* For all sample values

Table 2.6. Oxidisable C (%) values for four samples dates where three separate cores were analysed; P values are for the factors field (as listed for each year) and sample position (1, 2, and 3), standard error of the mean (SEM) is also presented, the tHSD value is provided for significant effects. Note: Different sets of fields were sampled with the three separate core method in the four years.

Time	September 1995	April 1996	May 1998	Dec. 1998	Dec. 1998
Depth, cm	**0-15**	**0-15**	**0-15**	**0-15**	**15-30**
Field code					
43	-	0.430	-	0.473	0.273
44	0.537	0.520	0.617	0.457	0.263
45	0.617	0.533	0.437	0.577	0.323
46	0.513	0.433	0.383	0.450	0.290
47	0.487	0.4367	-	0.450	0.270
48	-	-	0.54	0.523	0.290
49	0.380	0.560	-	0.547	0.303
50	-	-	-	-	-
51	-	0.380	-	0.500	0.310
52	-	0.460	-	0.417	0.363
531	0.487	0.440	0.557	0.440	0.293
532	0.487	0.480	0.363	0.493	0.347
533	0.483	0.347	0.390	0.523	0.373
534	0.583	0.500	0.403	0.443	0.270
N	27	36	24	39	39
Field P	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Sample position-P	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Grand mean*	0.508	0.460	0.461	0.484	0.305
SEM*	0.0204	0.0156	0.0363	0.0157	0.0098
tHSD	-	-	-	-	-

*For all sample values

Comparison of historical sampling and a more intensive method: 2010 samples

An evaluation of the value of the historical sampling method (a bulked sample from three cores) was made in November 2010 by comparing samples comprising of three and 10 bulked cores from each field. For the 0-15 cm zone, ox. C and total C values did not differ significantly between the two methods (Table 2.7a). For pH $CaCl_2$ the 10 core method had a significantly lower value (5.44) than the three core method (5.64). pH H_2O was lower from the 10 than the three core method but this difference was not significant ($P > 0.05$). However, for 15-30 cm for both pH analysis methods, values from the 10 core method were significantly lower than the values from the three core method (Table 2.7b). For ox. C and total C values for the 15-30 cm, depth did not differ significantly between the two sampling methods. For both depths, however, it was notable that SEM values were lower for values from the 10 core method.

Table 2.7. Mean values for oxidisable C (ox. C), total C, pH $CaCl_2$ and pH H_2O from analyses of samples collected from three and 10 bulked cores per field (n = 12) from a) 0-15 cm and b) 15-30 cm profiles. Values in brackets are the standard error of the mean. P values are the Bonferroni adjusted probability for a paired T-test.

a) 0-15 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Three cores	0.389 (0.0323)	0.547 (0.0397)	5.64 (0.0723)	6.45 (0.0469)
Ten cores	0.417 (0.0248)	0.524 (0.0244)	5.44 (0.0583)	6.33 (0.0284)
P	> 0.05	> 0.05	0.036	> 0.05

b) 15-30 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Three cores	0.265 (0.0239)	0.347 (0.0219)	5.58 (0.0441)	6.39 (0.0288)
Ten cores	0.264 (0.0116)	0.316 (0.0071)	5.42 (0.0505)	6.23 (0.0376)
P	> 0.05	> 0.05	0.029	0.004

Seasonal effects

Historical samples: The effect of the time of sampling, principally dry or early wet season samples, on pH and ox. C values were examined. Since not all fields were sampled at every sample date (see Appendix 2), comparisons were made by selecting any fields with consecutive sample dates and comparing results from mid-dry-early-wet season or wet-mid dry season sequences. The longest period of consecutive sampling (0-15 cm) of the same fields was available for seven fields for seven consecutive samples and three more consecutive samples following a break in 2001. Plots of field values for these sequences are shown for the 0-15 cm values (Figure 2.1). Only four of these dates included consecutive 15-30 cm samples.

Comparisons among fields were most variable for the 2001-02 period; however, for the earlier period (1997-2000) there were often general patterns among fields, when the pH and ox. C values for most fields either increased or decreased (Figure 2.1). For ox. C values, there were significant ($P < 0.05$) increases or decreases in values between the first and second, third and fourth, fourth and fifth, fifth and sixth and seventh to eighth sample. The values for the second and third samples also approached significance ($P = 0.0519$) (Table 2.8). For pH values, there was a significant increase in pH from May 1998 to December 1998 (third to fourth sample) and a significant decrease in pH from May 2000 to May 2001 (seventh to eighth sample). It was notable that single fields also had changes that differed from the majority of other fields, such as the pH of field 532 in 2001 and 2002.

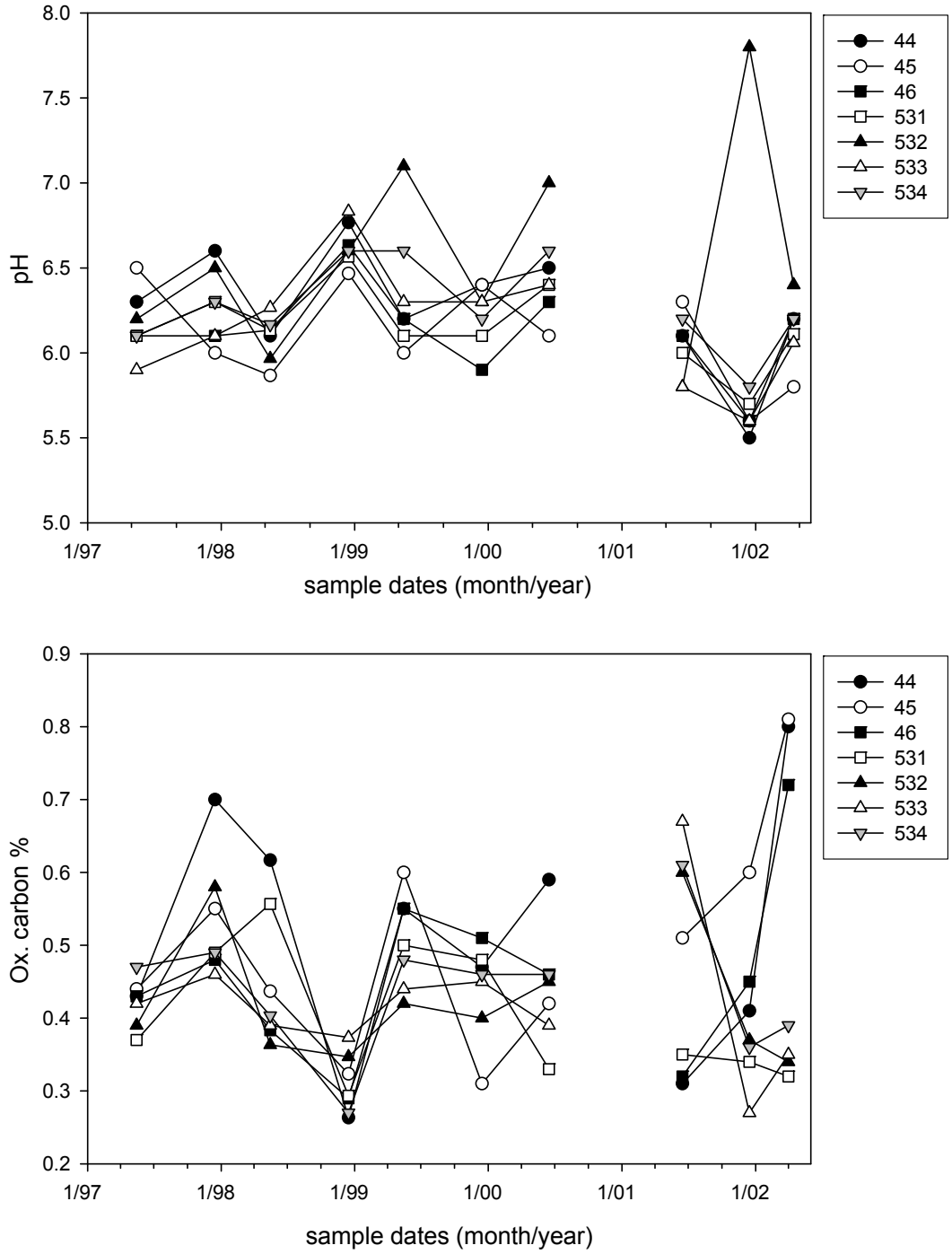

Figure 2.1. a) pH and b) oxidisable C (ox. C) values for the 0-15 cm zone for seven fields sampled consecutively in a dry season (May or June) and again in a following early wet season (December)

Table 2.8. Mean change of seven fields between consecutive samples for pH or oxidisable C (ox. C) values and significance levels (P values from the Wilcoxon Rank sum test) each comparison period is also classified as a dry-early wet (D-EW) or early wet-dry (EW-D) sequence

Period	**May 97 Dec 97**	**Dec 97 May 98**	**May 98 Dec 98**	**Dec 98 May 99**	**May 99 Dec 99**	**Dec 99 May 00**	**May 00 May 01**	**May 01 Dec 01**	**Dec 01 May 02**
Seasonal classification	**D-EW**	**EW-D**	**D-EW**	**EW-D**	**D-EW**	**EW-D**	**-**	**EW-D**	**D-EW**
Sample no.	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10
pH	0.10	-0.18	0.55	-0.28	-0.13	0.24	-0.43	-0.10	0.20
P	> 0.05	> 0.05	0.0225	> 0.05	> 0.05	> 0.05	0.0418	> 0.05	> 0.05
ox. C	0.11	-0.09	-0.14	0.20	-0.07	0.00	0.04	-0.08	0.13
P	0.0225	> 0.05*	0.0225	0.0223	0.0343	> 0.05	> 0.05	> 0.05	> 0.05

*P = 0.0519

For data from six fields (field 532 was excluded as 2001 pH values were greater than 1.96*SEM from the mean) sample-sequences were classified as dry to early wet (D-EW) or early wet to dry (EW-D) (as shown in Table 2.8) and were classified as having either a mean decrease, increase or no clear change (less than 0.05 mean change) in pH and ox. C values (Table 2.8). For mean soil pH change, two of the four EW-D sequences were associated with a decrease in pH and two of four D-EW were associated with increases in pH values. There was also no consistent association with the amount of rainfall and pH increases or decreases (data not presented).

For mean ox. C changes, two of four D-EW sequences were associated with a decrease and two of four EW-D were associated with increases in mean values. There were no consistent associations of sequence type (D-EW or EW-D) or rainfall (data not presented) with increases or decreases in mean ox. C values. The plotting of rainfall (mm) prior to D-EW sequences or from the period between the EW sample and D sample for EW-D sequences against seasonal changes in pH or ox. C showed no clear relationship for either pH or ox. C. The plotting of the seasonal pH change against seasonal change in ox. C also provided no clear or significant relationships (data not presented).

Recent samples: For the 2010 and 2011 samples, the effect of season of sampling on pH and ox. C values was determined. The 2010-11 wet season differed from the long-term average and had the highest rainfall of the 18 seasons for which soil analyses records span for this trial. Rains started earlier than usual that season with a total of 86 mm of rain over five days between the last week of September to 16 October before the trial area soil was sampled on 20 October.

At both depths, ox. C and total C percentage values were significantly lower after the wet in 2011 compared with before the wet in October 2010 (Table 2.9). For ox. C values, this was equivalent to a 36% and 28% reduction, and for total C this was equivalent to a 44% and 33% reduction, for the 0-15 cm and 15-30 cm depths, respectively.

Field 44 (pangola grass) had a marked decline in pH after the wet, but across all fields there was significantly higher pH $CaCl_2$ after the wet season compared with before at both 0-15 cm and 15-30 cm (Table 2.9 and Figure 2.2). There was no significant difference in pH H_2O between the pre and post wet season values. The scale of the difference in pH $CaCl_2$ was approximately 0.35 and 0.5 units for the 0-15 cm and 15-30 cm depths, respectively (Figure 2.2). For the pH H_2O, it was notable that values both increased and decreased in a number of different fields (Figure 2.2). A plot of change in pH (ΔpH) between pH $CaCl_2$ and pH H_2O verses conductivity showed that ΔpH values were higher in 2010 samples and that overall, conductivity values were mostly very low (Figure 2.3).

Table 2.9. Mean values from 12 fields for oxidisable C (ox. C), total C, pH $CaCl_2$ and pH H_2O for samples (10 bulked cores per field) collected at the end of the dry season, October 2010 (before the wet) and May 2011 (after the wet) from 10 bulked cores per field for a) 0-15 cm and b) 15-30 cm sample zones, including standard error of the mean P values are the Bonferroni adjusted probability for a paired t-test

a) 0-15 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Before wet, 2010	0.417 (0.0248)	0.524 (0.0244)	5.44 (0.058)	6.33 (0.028)
After wet, 2011	0.268 (0.0098)	0.294 (0.0083)	5.80 (0.102)	6.38 (0.104)
P	0.0001	< 0.0001	0.0140	> 0.05

b) 15-30 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Before wet, 2010	0.264 (0.0116)	0.316 (0.0071)	5.42 (0.051)	6.23 (0.038)
After wet, 2011	0.190 (0.0138)	0.211 (0.0151)	5.90 (0.138)	6.50 (0.147)
P	0.0003	< 0.0001	0.0051	> 0.05

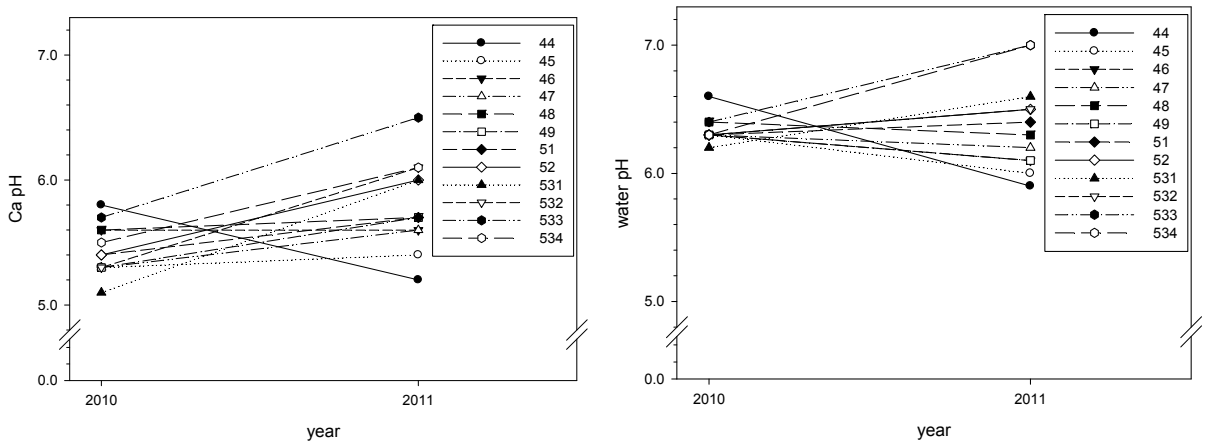

Figure 2.2. pH $CaCl_2$ method (left) pH H_2O method (right) values for 2010 and 2011 for the 0-15 cm sample zone with values for each of the 12 fields identified for both sample years

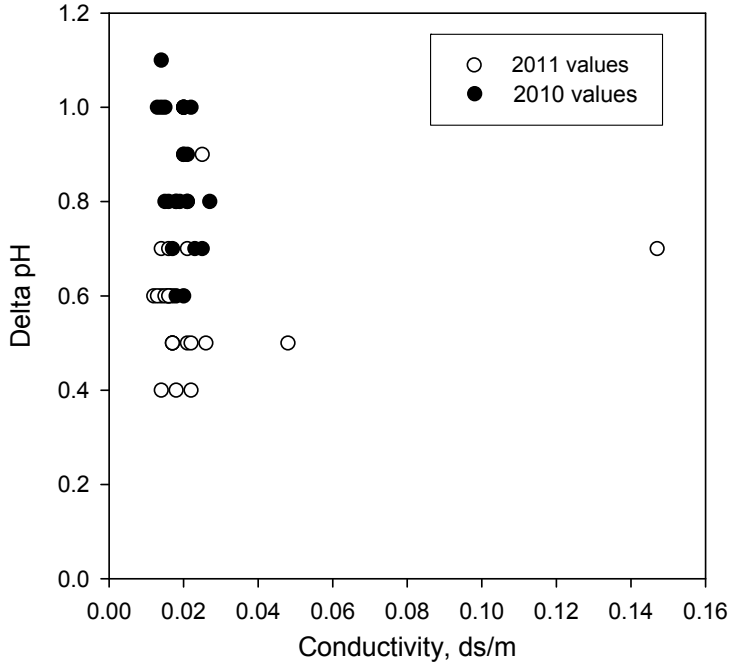

Figure 2.3. Delta pH (pH H_2O-pH $CaCl_2$) plotted against conductivity EC for 0-15 cm and 15-30 cm values from both sample years

2.2.3 Evidence for species or composition effects

Field comparisons based on multiple values per field

For the 9, 12, 8 and 13 fields sampled in 1995, 1996, and May and December 1998 an analysis of sample position and field effects are presented in Tables 2.5 and 2.6. For soil pH there was no significant field effect in 1995, 1996 or in May 1998, but for December 1998 field (d.f. = 24) had a significant effect for both the 0-15 cm (P = 0.0208, SE = 0.136, HSD = 0.668) and the 15-30 cm (P = < 0.0001, SE = 0.129, HSD = 0.637) depths. For the 0-15 cm samples, field 43 had a significantly lower pH than fields 44, 47, 48 and 533 and for the 15-30 cm samples, field 43 had a significantly lower pH than all other fields. Field 43 had silk sorghum and Maldonado for two years but was cultivated, fertilised and re-sown with silk sorghum and blue pea in December 1998. For ox. C, there was no significant field effect in any year (Table 2.6).

Pooled data from the three core and 10 sampling method for 12 fields sampled in 2010 was also used to examine for field effects. Ox. C, total C, $CaCl_2$ pH and water pH values for the 0-15 cm and 15-30 cm zone were analysed using a general linear model (GLM)with field as a dependant factor. There were no significant differences between fields for any of the measurements (ox. C, total C, pH $CaCl_2$ and pH H_2O values) (data not presented).

Field comparisons from composition groupings

The ability to compare legume-based pastures with non-legume pastures was limited as only two fields had grass (non-legumes only) species. The two grasses fields were pangola (field 44) and sabi (field 46). Two other fields had these grass species in a mix with legumes. They were fields 45 (pangola and leucaena) and 48 (sabi, Wynn cassia and leucaena). Due to the lack of evidence for differences between individual fields in the 12 fields sampled in 2010, formal analysis on this smaller set of four fields was not attempted. Instead, values from these fields of legume-grass or grass only categories were plotted. There were no consistent

trends at both sample depths for differing soil C (ox. C or total C) values. For pH comparisons, there was also no evidence of differences between the pasture categories.

Tree legumes and pastures: A comparison was made of soil C and pH between the tree legume leucaena and the grass-legume pastures in the same fields. For the 0-15 cm depth, there were no significant differences between ox. C, total C, and either pH method (Table 2.10). For 15-30 cm depth, both pH measures for leucaena were slightly lower than for the pastures, but these differences were not significant. However, for total C, the leucaena samples had significantly higher values (0.36 %) than the pastures in those fields (0.31%). There were no significant differences in ox. C values at this depth.

Table 2.10. Mean values (10 bulked cores/field) for oxidisable C (ox. C), total C, pH $CaCl_2$ and pH H_2O for samples from under leucaena (Lec.) in each field and from the pasture for fields 45 (pangola), 48 (sabi grass and Wynn cassia) and 534 (buffel) in each field, for a) 0-15 cm and b) 15-30 cm profiles. Values in brackets are standard error of the mean. P values are the Bonferroni adjusted probability for a paired t-test.

a) 0-15 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Lec.	0.413 (0.0379)	0.573 (0.0252)	5.60 (0.173)	6.37 (0.067)
Pasture	0.443 (0.0289)	0.597 (0.0115)	5.47 (0.088)	6.33 (0.033)
P	> 0.05	> 0.05	> 0.05	> 0.05

b) 15-30 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Lec.	0.200 (0.0400)	0.360 (0.0100)	5.37 (0.185)	6.20 (0.115)
Pasture	0.247 (0.0306)	0.310 (0.0173)	5.50 (0.058)	6.30 (0.100)
P	> 0.05	0.0494	> 0.05	> 0.05

2.2.4 Evidence for long term change

This section examines evidence for longer-term changes in the soil pH and C values. Long-term change is defined here as a change (increase or decline in values) evident over three or more seasons. Shorter-term seasonal effects were considered in Section 2.22. To avoid the effects of changes in pastures or substantial management changes, fields that did not have substantial changes in pastures during the sampling period were selected for examination in this section. These fields with the last year of pasture treatment change indicated in brackets were: 46 with sabi grass (pre-1990), 47 with Jarra and Crotalaria (1995), 49 with buffel and blue pea (1990), 51 with Strickland and Wynn cassia (1980) (see Tables 2.1 and 2.3 for more details). There were 16, 16, 16 and 14 sets of results for these four fields, respectively. Three additional fields (531, 532, 533) were also included for comparison as they had the same grass species (buffel) and the same legume (Wynn cassia), although this was self-established in two fields (532 and 533). The last year of pastoral composition changes in these fields was 1994. Comparisons focussed on the 0-15 cm sample zone as there were comparatively few 15-30 cm samples and none prior to 1998. Each of the 53 series fields had 15 sets of results.

Soil pH: long-term trends

All sample dates and pH H_2O values for these fields were plotted as shown in Appendix 3. Regression of the cumulative day count against pH values for all available years of data (analysis set 1) indicated no significant decline or increase in pH over the sampling period (Table 2.11). As an example, field 47 is shown in Figure 2.4a. However, it was notable that for five fields (46, 47, 49, 531 and 532) there was a weak (moderate r^2 values but were non-significant) downward trend in pH values over time, as shown for example

in field 47 in Figure 2.4a. For the other fields (51 and 532) there was no apparent increase or decline. It was also notable that the three buffel and Wynn cassia fields did not have similar values at all sampling dates, in particular field 532 differed with higher pH values for three dates.

However, one sampling date appeared to have a large influence on apparent trends for fields 46, 47, 49, 531 and 532, which was December 2001. All of the seven fields had the lowest observed pH values than at any other sampling date. As this value was the second or third to the last sample, depending on the particular field before the break in sampling before 2010 and 2011, it had a large effect on pre-2010 and 2011 trends.

Exclusion of the 2010 and 2011 pH values resulted in four fields (46, 47, 531 and 533) having significant declines in pH. This effect is shown for field 47 in Figure 2.4b (Table 2.11). However, exclusion of the December 2001 data in addition to the 2010 and 2011 data (analysis set 3) for fields with significant relationships in analysis set 2 resulted in only one of the four fields (531) having a significant decline in pH. Although P values for the regressions for two of these fields approached significance at the 95% level (Table 2-11), the example in Figure 2.4c showed that the December 2001 data had a large effect on pH trends in field 47.

Table 2.11. Multiple r^2 and P values for the linear regression of pH values as a dependant variable of the cumulative day count for each field for three data sets, 1 all data for each field, 2 data with the 2010 and 2011 data excluded, 3 data with the 2010, 2011 and December 2001 data excluded

	1. All data		**2. 2010 2011 excluded**		**3. Dec 2001, 2010, 2011 excluded**	
Field	Multiple r^2	P	Multiple r^2	P	Multiple r^2	P
46	0.3656	0.1638	0.6385	0.0140	0.5496	0.0517
47	0.3147	0.2352	0.5853	0.0279	0.4793	0.0975
49	0.3779	0.1490	0.4146	0.1405	-	-
51	0.0445	0.8800	0.3281	0.2978	-	-
531	0.2112	0.4499	0.7489	0.0032	0.6906	0.0129
532	0.0498	0.8602	0.1475	0.6305	-	-
533	0.1024	0.7165	0.6351	0.0197	0.5425	0.0684

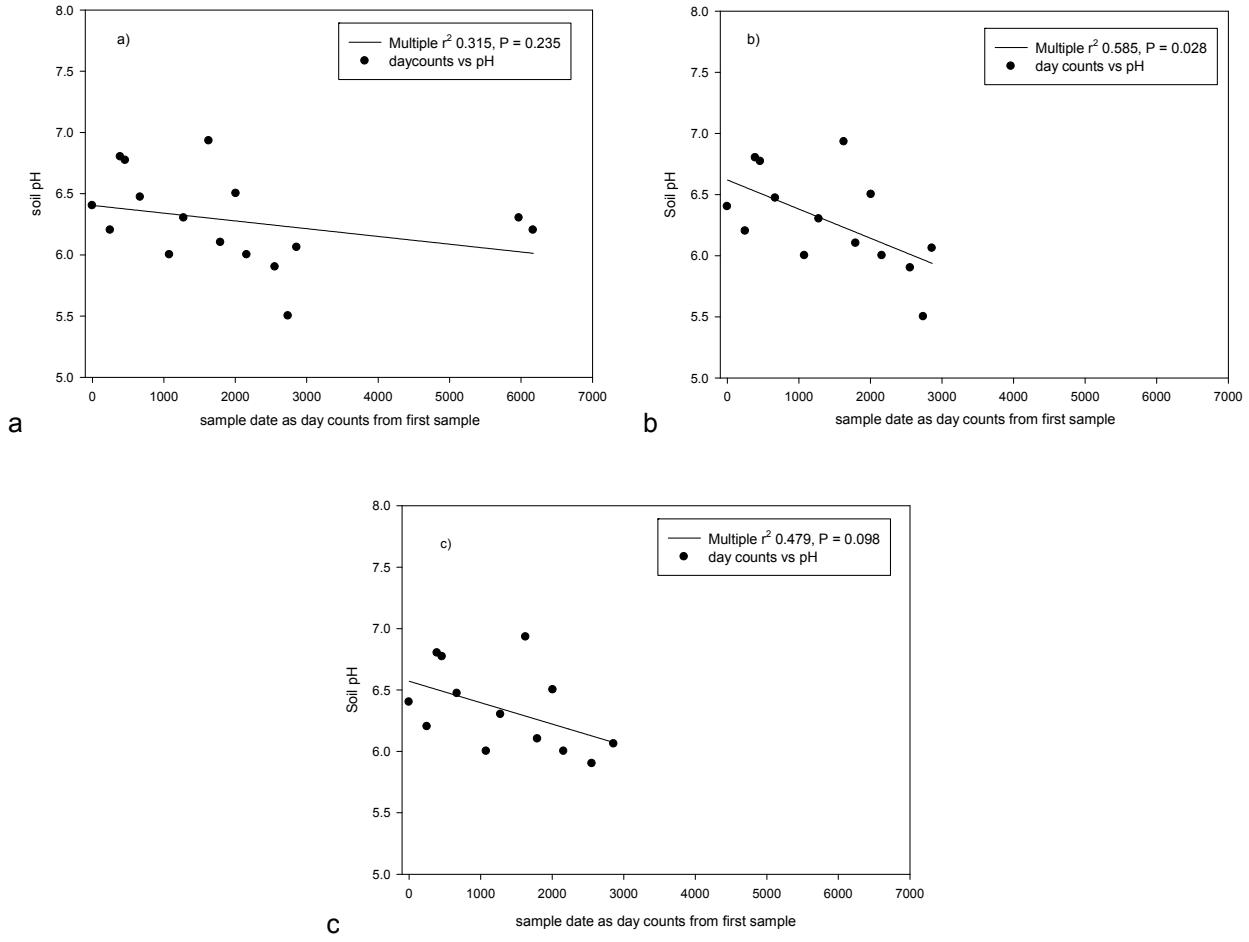

Figure 2.4. Plots of pH H_2O against sample dates as represented by cumulative day counts with linear regressions shown for one example (field 47) for a) all years of data b) data with 2010 and 2011 excluded and c) data with December 2001, 2010 and 2011 excluded. Significance values and multiple r^2 values are shown for each regression.

Oxidisable C: long-term trends

There were no consistent trends for increases or decreases for ox. C values across time. An example using field 46 is shown in Figure 2.5. Plots for all fields are shown in Appendix 3. A plot for field 51 is also presented as it had an apparent non-linear relationship with an increase in ox. C values from 1996 to 1999 then a decrease from 1999 to 2003. For all plots the 2010 and 2011 samples are indicated with a different symbol as these ox. C values were determined using the non-modified W-B method. All other values prior to 2010 were determined using a modified W-B method. An estimation of ox. C values for the modified W-B method from the 2010 and 2011 non-modified W-B method values were made by multiplying values by 1.27 (Meersmans et al. 2009) and are presented as an additional plot. The relationship between non-modified W-B method ox. C and total C values for the 2010 and 2011 samples indicated a correction factor of 1.18 for conversion of ox. C to total C (Figure 2.6).

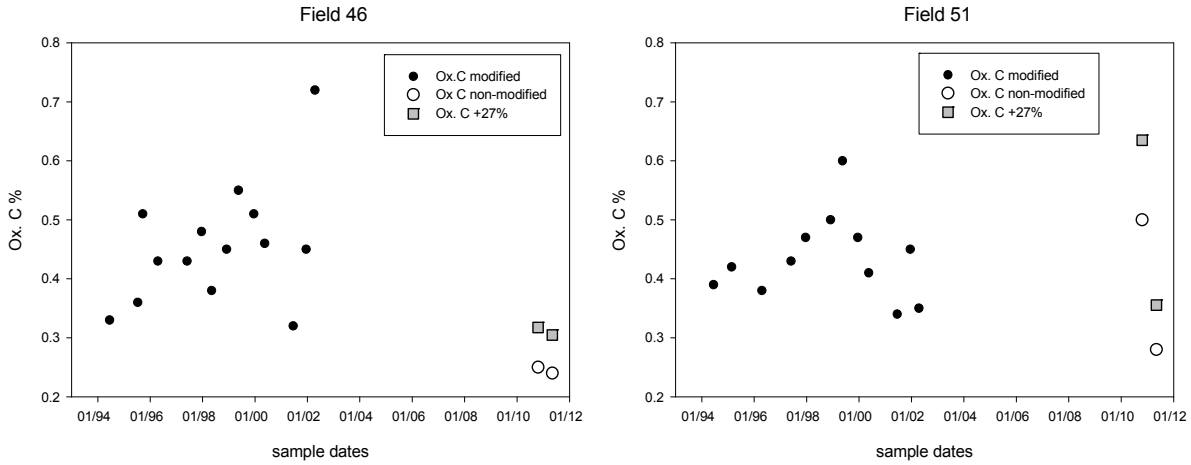

Figure 2.5. Oxidisable C (ox. C) % over time for fields 46 (left plot) and 51 (right plot) showing all 0-15 cm samples for samples from 1994 to 2011. The 2010 and 2011 results from a differing W-B method to prior samples are indicated in addition to values being corrected (*27%) for equivalence also being separately shown.

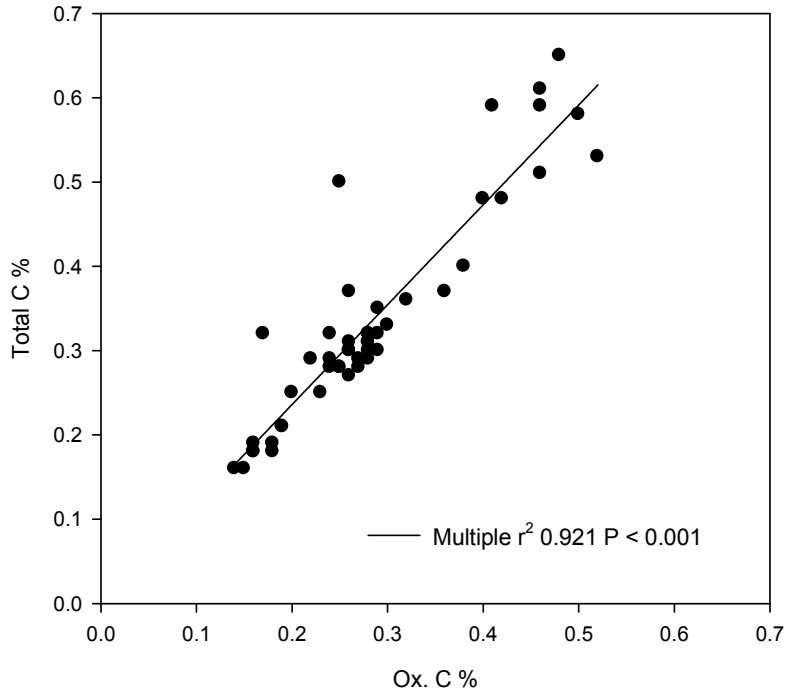

Figure 2.6. Plot of 2010 and 2011 0-15 cm and 15-30 cm oxidisable C data verses the total C data from the 10 core sample method for the 12 fields pasture (n = 48), linear regression details, y = 1.1845 (x) -0.0008, multiple r^2 = 0.9213, P < 0.001.

Regression analysis was only made on pre-2010 values due to the differing version of the W-B method used for analysis of the 2010 and 2011 samples (Table 2.12). Only field 47 had a significant regression. This is shown in Figure 2.7. For this field the relationship was significant and positive; however, the fitted regression

showed that this positive relationship would not have continued if the 2010 and 2011 corrected or uncorrected values were included.

Table 2.12. Multiple r^2 and P values for the linear regression of oxidisable C values as a dependant variable of the cumulative day count for each field with the 2010 and 2011 data excluded

	2010 2011 excluded	
	Multiple r^2	P
46	0.4445	0.1113
47	0.5857	0.0278
49	0.1978	0.4979
51	0.0160	0.9607
531	0.3722	0.2104
532	0.0216	0.9441
533	0.0070	0.9818

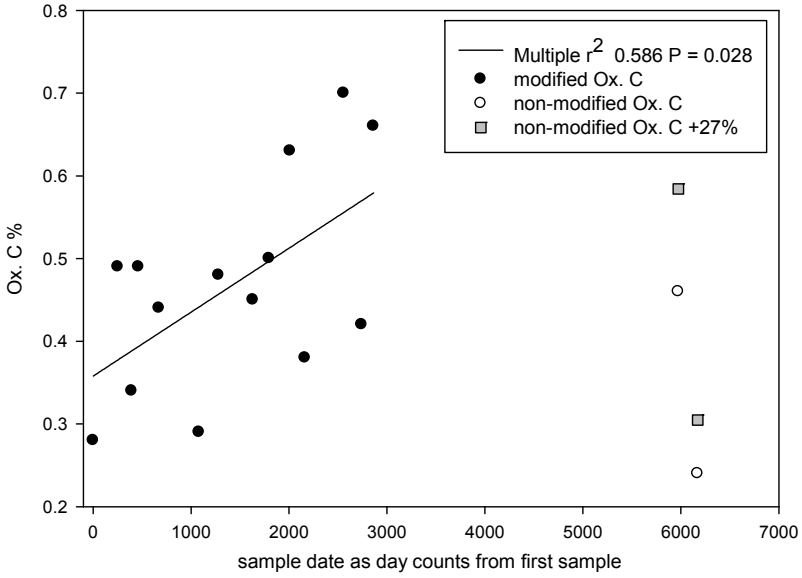

Figure 2-7. Oxidisable C (ox. C) % over time for field 47 showing all 0-15 cm samples for samples from 1994 to 2011. The 2010 and 2011 results from a differing non-modified W-B method to prior samples are indicated in addition to values being corrected (27%) for equivalence; they are separately shown. Regression fitted for pre 2010 data only, y = 0.001(x) + 0.3578.

Uncleared bush comparison with three selected pastures

There were no significant differences in C concentrations between the three buffel and Wynn cassia fields and the three bush areas for either analysis method or sample depth for 2010 samples (Table 2.13). Although the 0-15 cm ox. C value of 0.49 for the bush area in comparison with the buffel fields of 0.39 approached significance with a P value of 0.0652, for the pH $CaCl_2$ method for 0-15 cm samples, buffel fields had a significantly lower pH than the bush area. The values for the pH H_2O method and the pH $CaCl_2$ method at the 15-30 cm depth did not differ (Table 2.13).

Table 2-13. Mean values for oxidisable C (ox. C), total C, pH $CaCl_2$ and pH H_2O from analyses of samples collected in 2010 from three areas with adjacent uncleared bush and three species fields (531, 532, and 533) containing buffel grass and Wynn cassia from a) 0-15 cm and b) 15-30 cm profiles. Values in brackets are the standard error of the mean. P values are the Bonferroni adjusted probability using pooled variances for a two sample t-test.

a) 0-15 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Buffel fields	0.387 (0.0371)	0.537 (0.1126)	5.33 (0.0667)	6.33 (0.0882)
Bush area	0.490 (0.0173)	0.600 (0.0115)	5.93 (0.1202)	6.63 (0.1202)
P	> 0.05	> 0.05	0.012	> 0.05

b) 15-30 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Buffel fields	0.230 (0.0173)	0.333 (0.0321)	5.57 (0.088)	6.33 (0.120)
Bush area	0.223 (0.0252)	0.280 (0.0200)	5.47 (0.145)	6.33 (0.033)
P	> 0.05	> 0.05	> 0.05	> 0.05

In comparisons of 2011 values between the bush area and buffel fields, both C concentrations and pH did not differ significantly regardless of analytical method (Table 2.14).

In all the 2011 samples, C concentrations in both the bush area and buffel fields were lower than in the 2010 samples. In contrast to C concentrations, the pH of the bush area at the 0-15 cm depth was the same or very similar between the 2010 and 2011 sampling dates, while the pH values increased in the buffel fields from the 2010 to 2011 sampling dates. A notable seasonal and site effect was for the 2010 bush samples. The pH values were higher in the 0-15 cm zone than in the 15-30 cm zone, while for buffel fields in 2010, the 0-15 cm zone had a lower pH than the 15-30 sample zones; but for both the bush and buffel fields in 2011 after the wet season, there was little evidence of differences in pH between the two sample zones.

Table 2.14. Mean values for oxidisable C (ox. C), total C, pH $CaCl_2$ and pH H_2O from analyses of samples collected in 2011 from three areas with adjacent uncleared bush and three species fields (531, 532, and 533) containing buffel grass and Wynn cassia from a) 0-15 cm and b) 15-30 cm profiles. Values in brackets are the standard error of the mean. P values are the Bonferroni adjusted probability using pooled variances for a two sample t-test.

a) 0-15 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Buffel fields	0.260 (0.0153)	0.283 (0.0176)	6.20 (0.153)	6.70 (0.153)
Bush area	0.333 (0.0338)	0.373 (0.0448)	5.93 (0.120)	6.60 (0.058)
P	> 0.05	> 0.05	> 0.05	> 0.05

b) 15-30 cm	ox. C (%)	Total C (%)	pH $CaCl_2$	pH H_2O
Buffel fields	0.210 (0.0404)	0.230 (0.0451)	6.40 (0.404)	6.97 (0.470)
Bush area	0.150 (0.0058)	0.160 (0.0058)	6.03 (0.120)	6.70 (0.100)
P	> 0.05	> 0.05	> 0.05	> 0.05

3 ROTGUT TRIAL

A tillage study called the 'Rotation of tropical grains under different tillage methods' was started in 1984 and continued to 2000. The acronym Rotgut was used to describe this study. The study compared no-tillage (nt) drilling to conventional cultivation (ct) and drilling method for wet season crop production at DDRF. Over the years, crop yields and crop nutrient concentrations results from different crops and nutrition management practices were reported from this study (Thiagalingam et al. 1991a; Thiagalingam et al. 1991b; Thiagalingam et al. 1994; Thiagalingam et al. 1995; Thiagalingam et al. 1996). One report included an observation on soil quality in terms of soil C, the ox. C concentrations for the nt treatment in the 0-5 cm zone (1.05%) was 40% higher than for the ct (0.63%) treatment, in a comparison of samples collected eight years after the trial had started (1991-92 season) (Thiagalingam et al. 1996). It was also observed that a decline in soil pH independent of tillage treatment had also occurred at this eight-year time-point since the start of the trial. In this case, the 1991-92 soil pH of ~6.1 indicated a decline from an initial pH of 6.8 (Thiagalingam et al. 1994).

Soil samples were also collected in 1996 from an uncleared area of bush adjacent to the trial with the same soil type. A number of additional soil results are now available, including results up to the year 2000 when the trial was ceased. Additional results to those cited above include samples from 1992, 1993, 1995, 1996, 1997, 1998, 1999 and 2000.

Overview of the trial and the soil quality report focus

Where possible, factors identified as affecting soil pH or soil C concentrations in tillage and semi-arid or tropical cropping trials from other Australian or international studies were investigated (Moody and Aitken 1997; Dalal and Carter 2000; Guzman et al. 2006; Fenton and Helyar 2007; Thomas et al. 2007). The trial provided an opportunity to investigate the effects of tillage practices and urea application on soil pH and ox. C concentrations. A comparison was also made of soil pH, bulk density and ox. C of soil from an uncleared area adjacent to the trial.

3.1 METHODS

Trial area

Lucas (1984) described three sections (Blocks A, B and C) of the Tippera Experimental Site. The area is about 50 m above sea level. The Rotgut trial was located in Block B in bay DPP6 (also called Bay 15 by DDRF staff, Bruce Sawyer, pers. comm.). Block B was in native woodland until cleared in 1981. These woodlands were composed mainly of *Eucalyptus folesheana*, some *Eucalyptus contertiflora* and *Eucalyptus tectifica*. The grasses included *Sehima nervosum*, *Themeda australis* and *Heteropogon contortus* (Lucas 1984). It was also noted that prior to clearing in various areas at different times, the three blocks were used for rough grazing of unimproved native pasture (Lucas 1984). Following clearing, the trial area was sown with verano (*Stylosanthes hamata*) and sirato (*Macroptilium atropurpureum*) pasture before the trial establishment (Thiagalingam et al. 1991a).

Soil information

The soil type of bay DPP 6 at the experimental site was described as a Tippera clay loam (key Gn 2.12) (Lucas 1984) (Appendix 4). An intensive survey of approximately 12 hectares of 'Tippera' soils in which the trial was located had mapped the distribution of differing 'Tippera' soils and their various profiles, including that of the Tippera clay loam at the Rotgut experimental site in bay DPP 6 (Lucas 1984). These soil descriptions of Block B were carried out in 1979 and in June 1982 (Lucas 1984). Results from intensive surveys of the area in 1979 and 1982 were collated to provide information for the representative profile descriptions described by Lucas (1984).

This soil was then described in reports as a Rhodic Paleustalf and noted to have a strong hard-setting surface (Thiagalingam et al. 1991a). Australian soil classification systems have changed since the 1990s and to our knowledge this soil has not been re-described. However, an example of a 'Tippera' from the Douglas Daly was described using the current Australian soil classification system (Hill et al. 2011). This soil had a general description as a Clay Loamy Red Earth and has the Australian soil classification as a Deep Red Mesotrophic Kandosol.

Trial design and management

The trial site and design have been previously described in some detail in previous publications (Thiagalingam et al. 1991a; Thiagalingam et al. 1996). Briefly, the trial comprised three replicates of two treatments (1. nt drilling and 2. ct and drilling) used for rain-fed wet season crop establishment. Plot sizes were 69 m wide by 54 m long arranged in a single row. The ct was based on primary cultivation with offset discs followed by a chisel plough fitted with finger harrows. The ct drilling was based on the use of a John Shearer Trash Culti Drill. The nt drilling was based on the use of a Buffalo no till planter (Thiagalingam et al. 1991a). Cultivation depths were between 200 to 400 mm, depending on the soil moisture conditions. Fertilisers were banded at sowing (~70 mm below the seed and 100 mm to the side of the seed) with additional topdressing used in one season only. Wet season crops were typically sown from mid-December through to the first week of January after sufficient rains. The specific time of sowing was dependant on the timing of the first rains that season. At the start of the 1993-94 wet season, the trial was initiated with a wet season crop of maize (Table 3.1). The objective of the maize crop was to deplete N from the previous pasture legumes (Thiagalingam et al. 1991a). GPS corner points of the trial area were S 13°50.151, E 131°13.618; S 13°50.184, E 131°13.613; S 13°50.190, E 131°13.849; S 13°50.222, E 131°13.844.

For the seasons of the study from 1984 to 1988, main plots were divided into sub-plots with differing rotation and sub-sub plot N fertiliser treatments. A split-plot approach was used for management and analysis. After that period, split plot treatments were not imposed with some exceptions. During the 1992-93 season, two soybean cultivars were sown as a split-plot treatment in each plot. During the 1995-96 season three application rates of urea were used within each plot (0 kg/ha, 70 kg/ha and 140 kg/ha) as split plot treatments.

In the first experimental phase of the four seasons from 1984-85 to the 1987-88 seasons, maize and soybeans were rotated or grown continuously as split plot treatments. Crop yields and nutrient concentrations for this four-year experimental period were summarised by Thiagalingam et al. (1991a). Annual fertiliser applications were included at basal rates to all plots and an additional N treatment was applied for maize (see Table 3.1). Examples of fertilisers and rates are provided for two of these seasons. For the 1986-87 season, a basal fertiliser of P (Topfos, 25% super with Cu, Zn and Mo), K (muriate of potash), S (copper sulphate monohydrate), Zn, Cu (copper sulphate) and Mo (sodium molybdite) at 30, 50, 50, 5, 5 and 0.2 kg/ha, respectively was applied (Thiagalingam et al. 1987). For the 1987-88 season rates were similar at 30, 25, 30, 5, 5 and 0.2 kg/ha for P, K, S, Zn, Cu and Mo, respectively (Thiagalingam et al. 1988).

Following the first phase, a second phase was established with the tillage treatments maintained and a single crop was then grown each season (see Table 3.1). This second stage started in the 1988-89 season and finished in the 1992-93 season (Thiagalingam et al. 1994). For this phase, plots received an annual basal fertiliser of muriate of potash and single superphosphate (with Zn, Cu and Mo) providing 25 kg K, 30 kg P, 30 kg S, 5 kg Zn, 5 kg Cu and 0.2 Mo/ha. Cereals (sorghum and maize) also received an extra 80 kg/ha of N as urea. For the final season of this phase, 1992-93, two soybean cultivars were sown as a split-plot treatment in each plot. Yield and crop nutrient information were reported for some seasons of this phase by Thiagalingam et al. (1994).

A third phase was then started in the 1993-94 season and continued until the 1999-2000 season. Again the tillage treatments were maintained and a single crop was sown in each plot. A single fertiliser rate was used each year during this phase with the exception of the 1995-96 season when three application rates of urea (0 kg/ha, 70 kg/ha and 140 kg/ha) were established as split plot treatments. For the 1997-98 and 1999-2000 seasons a 19.13.0.9 fertiliser was applied. This was considered to be in the form of diammonium phosphate (DAP, $(NH_4)_2HPO_4$) blended with sulphate of ammonia (P. Hausler, pers.comm.).

Soil sampling methods

This section details the soil sampling methods for sampling events where analytical results were currently available. This was for samples from 1992 to 2000. The trial started in 1984 and the first record of soil sampling was after the 1985-86 season (Thiagalingam et al. 1987). However, the earliest soil analyses results from the trial that could be located were those collected after the 1991-92 season (Thiagalingam et al. 1994). The previous records have been lost. During the early period of the trial, soil collection methods were based on the collection of four randomly selected samples per main plot with the bulking of post-harvest samples to provide one sample for analysis per plot (Thiagalingam et al. 1987).

For the results detailed in this report unless otherwise stated, sampling was carried out at each site by hand auger (34 mm diameter). Samples from each zone of the four sites in each plot were bulked to provide a single sample from each zone for each plot. Samples were air-dried, ground and sieved (1.2 mm aperture sieve) before analysis at the DPIF soils laboratory in Darwin.

For the 1992-93 season, two varieties of soybean (Buchanan and Leichart), were sown as a split plot treatment. Two soil samples were collected separately in each split plot and bulked. Separate analyses were made for the samples from each variety. For the purposes of this report, the results from each of the two split plots were averaged for each main plot. Soil sampling occurred after the sowing but generally before the harvest of a crop (May 1995, February 1996, April 1997, April 1998 and June 1999). The objectives of the timing of these sample dates were to identify the soil fertility levels at the end of the growing season.

Table 3.1. Summary of wet season crops and subplot treatments for 18 seasons in the Rotgut study methods and soil sampling dates if available

Treatments	Fertiliser	Season
Cover crop of maize	300 kg/ha of super, potash, copper, zinc and molybdenum and 40 N kg/ha as urea.	83-84
Sub-plots of continuous maize, maize/soybean, soybean/maize, or continuous soybean	Pre-plant soil samples were collected two weeks before crop sowing (usually mid Dec) at depths of 0-10, 10-30 and 30-60 cm from the 0 and 80 N treatments in the verano and sirato leys. Five levels (0, 20, 40, 80, and 160 kg ha) of N (ammonium nitrate, Nitram 34%) as banded applications to the maize subplots only (Thiagalingam et al. 1987).	84-85
Sub-plots of continuous maize, maize/soybean, soybean/maize, or continuous soybean	As described for 1984-85.	85-86
Sub-plots of continuous maize, maize/soybean, soybean/maize, or continuous soybean	As described for 1984-85 (Thiagalingam et al. 1987).	86-87
Sub-plots of continuous maize, maize/soybean, soybean/maize, or continuous soybean	As described for 1984-85, except prilled urea (46% N) was used for the 1987-88 season (Thiagalingam et al. 1988). Post-harvest soil samples also included an additional sampling depth of 60-90 cm.	87-88
Grain sorghum	Annual basal fertiliser of muriate of potash and single super (with Zn, Cu and Mo) providing 25 kg K, 30 kg P, 30 kg s, 5 kg Zn, 5 kg Cu and 0.2 Mo/ ha (Thiagalingam et al. 1994). Sorghum and maize also received an extra 80 kg/ha of N as urea during the 1988-89 to 1991-92 period.	88-89
Maize	As described for 1988-89	89-90
Soybean	As described for 1988-89	90-91
Maize	As described for 1988-1989 including 0 and 80 N treatments (Thiagalingam et al. 1994). Soil samples (0-5, 5-15, and 15-30 cm) from 80 N treatments on 27/5/92 (Thiagalingam et al. 1994)	91-92
Soybean	As described for 1988-1989 (Thiagalingam *et al.* 1994). Two varieties Buchanan and Leichardt. Soils 5/5/1993	92-93
Maize	Top-dressed with 20-10-0-0 @ 130 kg/ha on the 19/1/1994	93-94
Mungbean cv. Putland	200 kg/ha of single super phosphate with Cu, Mo and Zn. Soils 10/05/1995	94-95
Grain sorghum	Pre-emergent application of 130 kg/ha NPKS (0-16.6-0-9.6) and three rates of urea within each plot (0 kg/ha, 70 kg/ha and 140 kg/ha). Soils, 70 and 80 N plots 8/2/1996, 0 N 4/3/1996.	95-96
Calvalcade	200 kg/ha NPKS (0-11-20-6) with 0.5% Cu, 0.5% Zn and 0.015% Mo. Soil 15/04/1997	96-97
Maize	Pre-planting 200 kg/ha of NPKS (19-13-0–10), then a top dress in January 1998 with urea at 120 kg/ha. Soils April 1998.	97-98
Soybean	Pasture gold® 150 kg/ha NPKS (0-14-0-17). Soils June 1999.	98-99
Forage sorghum	Pre-planting 200 kg/ha NPKS (19-13-0-9). No additional urea applied to sorghum. Soils 31/05/2000	99-00
Sabi grass	Goldphos 20® 50 kg/ha NPKS (0-16-0-20) applied in January 2001. Tillage treatments ceased, all ploughed for sabi preparation due to major weed problems at site, especially in the conventionally tilled treatment	00-01

For the 1995-96 season, samples were collected in 1996 separately from the nil urea subplots (0 N treatment) and a separate set of samples was collected from both the 70 and 140 kg/ha urea subplots. The combined samples from the two 70 and 140 kg/ha treatments were then termed ‘mixed N’ samples. For these samples two top zones (0-5, 5-15 cm) were collected with a hand auger (34 mm D) and a hydraulic auger (44.5 mm D) was used to collect deeper sample zones (15-30, 30-60, 60-90 and 90-120 cm).

The sampling of soil from an uncleared adjacent bush area was also made in 1996 (6 January). This bush area was about 250 m from the trial. The approximate GPS location of this bush area was S 13°50.337, E 131°13.847. Soil samples for fertility analysis were collected from three sample areas in the bush. Each area was about 25 m apart. At each of the three sample areas, three cores were collected and the samples were bulked for analysis.

On 8 January 1996 soil sampling of the Rotgut trial and the bush area was carried out to determine bulk density. For these samples the 44.5 mm diameter hydraulic corer was used for sampling. The depth zones sampled were the same as those described for 1996. In each Rotgut main plot two separate samples were collected. In addition, a single sample was taken from each of the three sample areas in an adjacent bush area.

Each sample was weighed wet after collection and a subsample (~120 g) of each was dried (as previously described) and used to determine the moisture content and dry weight. The bulk density was calculated by dividing the dry weight of each sample by the soil volume (Dalgliesh and Foale 1998). The core diameter and length of the sample zone were used to calculate soil volume for each soil sample zone. The method for calculating the C content of soils on a m^2 basis was as described by McKenzie et al. (2000) with the dry weight of the total sample from each zone multiplied by the bulk density to give kg ox. C/m^2 per sample zone. In addition m^3 values were calculated for comparing contents at different depths.

Analysis

The effects of tillage treatment (conventional vs. no till), N (mixed N, no N) and sample depth for percentage ox. C, bulk density and pH were analysed using general linear models (split-plot ANOVA with tillage main plots, fertiliser sub-plots and measurements through the depth profile repeated over time). Where comparisons were done with untreated bush plots, the tillage/N treatment combinations were flattened to a single factor and crossed with depth. In all models, the comparison of means was done using Tukey's HSD test.

3.2 RESULTS

3.2.1 Weather during the sampling period

Compared with long-term average rainfall data (1968-2011, 1067 mm) the four months of peak rainfall (December to April) and annual seasonal rainfall (1 July to 30 June) for the nine cropping seasons had a similar average rainfall (1143 mm). However, actual values around this mean varied quite widely (Table 3.2). Four seasons were considerably wetter than average and two considerably drier with three close to average (± 100 mm). However, the percentage of rainfall occurring from December to April for these nine seasons was within 10% of the average long-term average of 90.3% (range 83.8-99.0%). This indicated that the monthly timing of the rainfall was more similar to long-term averages than the amount of rainfall for these seasons.

Table 3.2. Rainfall recorded at DDRF during the trial period discussed in this report (1991-2000) for the long-term average wettest months, 1 December to 30 April and annual seasonal rainfall (1 July to 30 June) and the December to April rain as a percentage of annual seasonal rain, including mean, standard deviation and CV for the nine seasons in the study period

	Dec.-Apr.	June-July	% wet of annual
Average for 1968-2011	1067.4	1182.7	90.3
1991-92	781.8	929.2	84.1
1992-93	1219.2	1302.1	93.5
1993-94	1118.7	1130.5	99.0
1994-95	782.9	849.6	92.1
1995-96	965.1	1096.7	88.0
1996-97	1064.2	1269.2	83.8
1997-98	1595.6	1695.8	94.1
1998-99	1472.3	1590.6	92.6
1999-2000	1289.5	1449.4	89.0
Mean	1143.3	1257.0	90.7
Std. dev.	282.6	286.8	4.95
CV	0.247	0.228	0.054

3.2.2 Oxidisable carbon comparisons

Percentage oxidisable carbon

For the 0-5 cm zone there was a significant interaction ($P<0.05$) for tillage by year (Figure 3.1), in addition to both main effects being significant (tillage, $P<0.01$, year $P<0.001$) (Table 3.3). The interaction was due to both tillage treatments having very similar ox. C values in 1995. But for other sampling years the nt treatment had significantly higher ox. C values. The difference between the nt and ct ox. C values in this surface sample zone was about 0.25%.

For the 5-15 cm zone, there were significant differences ($P<0.05$) in ox. C concentrations between tillage effects in different years (Figure 3.2). In addition, values differed significantly ($P<0.001$) between years, but there was no significant main effect for tillage (Table 3.3). The interaction was due to the ct treatment having a higher ox. C content than the nt in 1995; but for 1997 this ranking reversed. Following 1997, ox. C values remained slightly higher under nt management but this difference between treatments was not significant for this sample zone.

For the 5-15 cm zone, there was no significant interaction between tillage and year (Figure 3.3) but there were significant differences between tillage ($P<0.001$) and year ($P<0.001$). For tillage, the nt plots had higher ox. C contents than the ct plots, with a difference of ~0.075% between these treatments (Table 3.3).

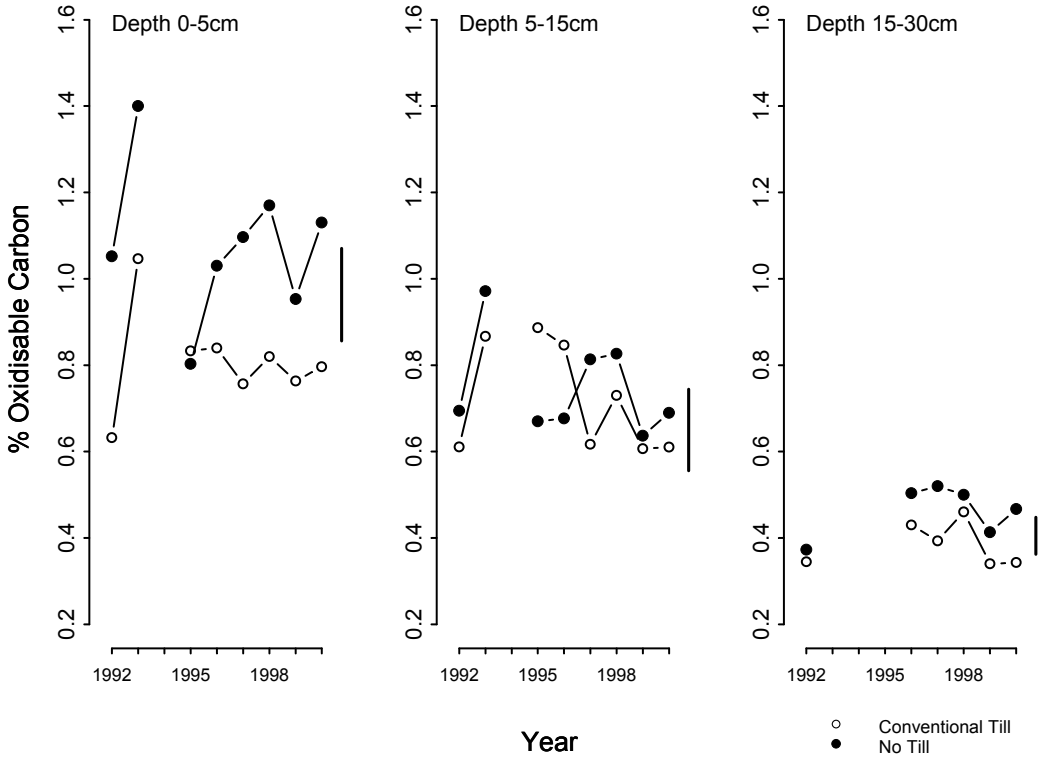

Figure 3.1. Values for oxidisable C (%) for tillage treatments (conventional and no till) for samples from the 0-5, 5-15 and 15-30 cm zones. Error bars are Tukeys HSD values (0-5, 0.2142, 5-15, 0.1887 and 15-30 cm, 0.0855) for comparison of means between treatments and years.

Table 3.3. Values for oxidisable C (%) for tillage treatments no till (nt) and conventional till (ct) for samples from the 0-5, 5-15 and 15-30 cm zones. Tukeys HSD values (tHSD).

	0-5 cm	**5-15 cm**	**15-30 cm**
nt	1.079	0.747	0.461
ct	0.811	0.722	0.385
tHSD	0.2572	0.1953	0.0404

1996 urea fertiliser effects on oxidisable C

In 1996, samples were collected from split plots treated with nil additional N (No N) or 70 and 140 kg/ha of urea applied (Mixed N). Comparison of ox. C contents in relation to tillage and N treatments among sample zones gave a number of interactions. Depth was a significant ($P < 0.001$) factor for the top five sample zones whereby each zone had significantly lower ox. C than the zone immediately above, with the exception of the 60-90 cm and 90-120 cm zones for which ox. C concentrations did not differ (Table 3.4). However, tillage ($P < 0.001$) (Figure 3.3) and N treatment ($P < 0.05$) (Figure 3.4) both significantly interacted with depth.

Table 3.4. Oxidisable C (ox. C) % by depth for 1996 samples, SED = 0.0542.

Depth (cm)	ox. C
0-5	1.046 e
5-15	0.868 d
15-30	0.499 c
30-60	0.313 b
60-90	0.242 a
90-120	0.211 a

In the depth by tillage interaction, there was a significantly greater ox. C concentration in the nt treatment in the 0-5, 15-30 and 60-90 cm sample zones. The greatest difference was in the 0-5 cm zone with 1.24% in the nt and 0.85% in the ct treatment (Figure 3.2). Counter to this trend, the higher nt ox. C concentration was in the 5-15 cm zone in the ct treatment (0.91%), which had a significantly higher ox. C concentration than the nt treatment (0.83%). There was no significant tillage effect at the 30-60 and 90-120 cm sample zones.

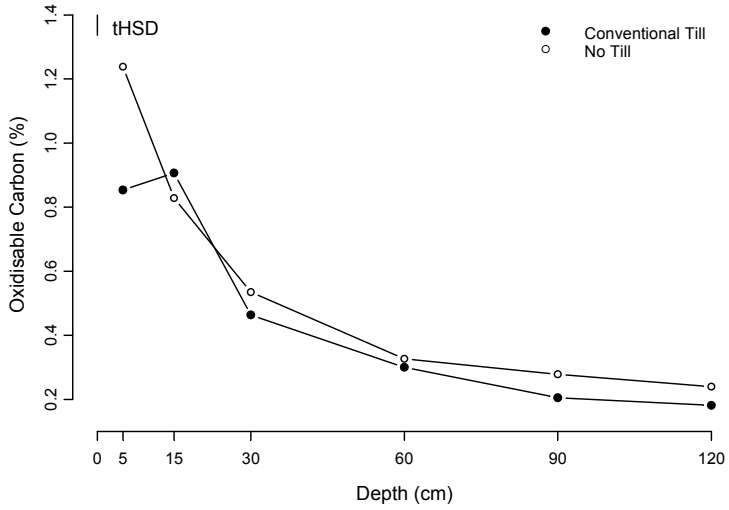

Figure 3.2. Values for oxidisable C for tillage treatments (conventional and no till) presented by sample depth, tHSD 0.0634

For the interaction between depth and N treatment the mixed N treatment had significantly lower ox. C concentrations in the 0-5, and 5-15 cm sample zones than the No N treatment (Figure 3.3). Mixed N treatment values were also higher at deeper sample zones but were not significant.

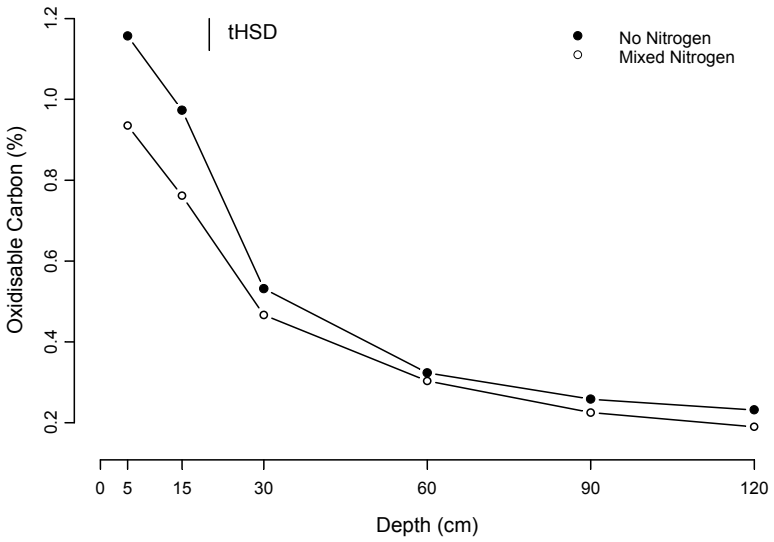

Figure 3.3. Values for oxidisable C for N treatments (no additional N and additional mixed N) presented by sample depth, tHSD, 0.0787

N treatment was also a significant (P < 0.01, tHSD 0.0522) main effect whereby the 0 N plots had a higher ox. C (0.579%) content than mixed N plots (0.480%), but N treatment also interacted significantly with tillage (P < 0.05) and with depth as described above. Of the three significant interactions the depth by tillage interaction had the strongest effect (F = 24.44) (Figure 3.4). The interaction was due to the nt 0 N plots having a higher ox. C content (0.652%) than the ct 0 N plots (0.507%). In contrast, for the mixed N treatment the nt plots (0.497%) had a higher ox. C content than ct plots (0.463%); but this difference was not significant. In addition, the ox. C content was significantly higher in nt 0 N plots than nt mixed N plots. This was not the case for the ct N treatments.

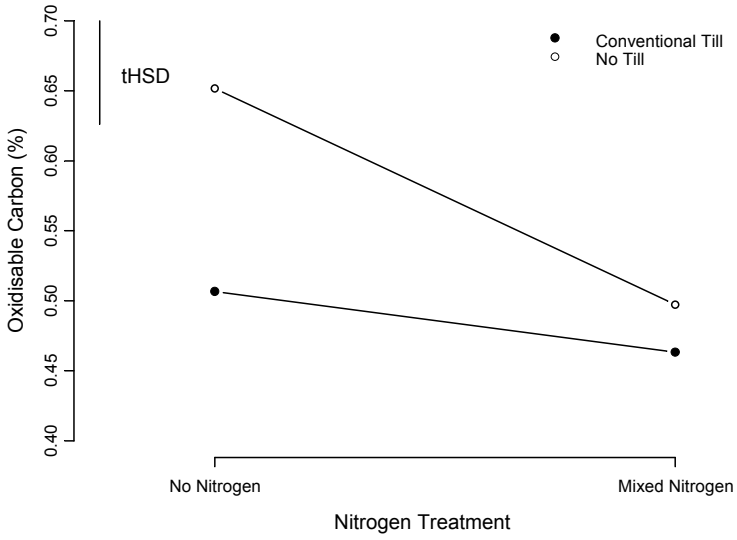

Figure 3.4. Values for oxidisable C (%) for N treatments (No N and Mixed N) and tillage treatments, Conventional and No-till, tHSD = 0.0737

Percentage of ox C in Rotgut plots in comparison with adjacent uncleared bush

A group based ANOVA comparison of the ox. C concentrations of the four Rotgut treatments and the bush area gave a significant ($P < 0.001$) interaction for the five treatments and depth (Figure 3.5). The interaction was due to differences between treatments among the top three sample zones.

For the 0-5 cm zone, the nt 0 N treatment (1.447%) had a significantly higher ox. C content than the other three Rotgut treatments and the bush area (1.093%). The bush area also had higher ox. C. concentrations than the ct mixed N treatment (1.030%) but did not have higher ox. C. concentrations than the other Rotgut treatments.

In the 0-5 cm sample zone, both the nt and ct 0 N treatments had higher ox. C values than their respective nt and ct mixed N treatments. This also occurred at the 5-15 cm sample zone for nt treatments but not for ct treatments.

For the 5-15 cm zone, the ox. C contents in the nt 0 N, nt mixed and ct 0 N treatments were all similarly high, for the two treatments with the highest values (nt 0 N and ct 0 N). These were higher than the ox. C values in the bush area.

For the 15-30 cm zone, treatment rankings changed with values for the ox. C contents of the bush area (0.907%) being higher than all Rotgut treatments with values of nt 0 N, 0.567%, nt mixed N, 0.503%, ct 0 N, 0.497%, ct mixed N, 0.430%, and nt mixed N, 0.503%. At the 15-30 cm zone, there were no differences in values between Rotgut treatments. This trend continued at all subsequent deeper sample zones (30-60, 60-90 and 90-120 cm) and ox. C values for the bush area and Rotgut treatments did not differ at these zones.

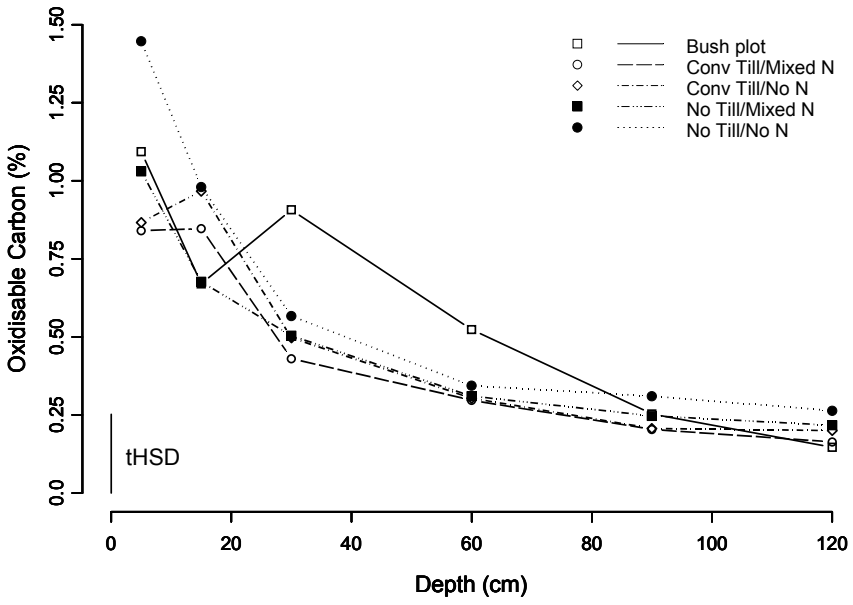

Figure 3.5. Soil oxidisable C (%) by depth for samples from an uncleared bush area and samples from the Rotgut trial: no-tillage 0 additional N; no tillage 70 and 140 kg additional N; conventional tillage 0 additional N; and conventional tillage 70 and 140 kg additional N. tHSD = 0.2519.

Bulk density, volumetric and area based C comparisons

The bulk density of plots in the Rotgut trial was not significantly affected by tillage. Respective mean values for ct and nt treatments were 1.540 and 1.546 g/cm^3 (tHSD 0.3978), but there was a significant ($P < 0.001$) depth effect (Table 3.5). Depth effects were pronounced between the top two zones, as the bulk density values were significantly lower at the surface 0-5 cm zone (1.448 g/cm^3) than at any other zone. In contrast, the 15-30 cm zone underneath had a higher value at 1.638 g/cm^3 than all other sample zones (Table 3.5). A comparison of the bulk density values for the two tillage treatments and those from the uncleared bush area provided a significant interaction ($P < 0.05$) for depth by group (ct, nt and bush) (Figure 3.6). Both the nt and ct treatments had higher bulk densities than the bush area for the 0-5 and 5-15 cm zones. For the 0-5 cm zone the ct treatment had a higher value than the nt treatment, but this ranking was reversed for the 15-30 cm zone. For the 15-30 cm zone the nt treatment also had a higher bulk density than the bush area. For the 30-60 cm zone the ct treatment had a lower bulk density value than both other treatments, and for the bottom two sample zones the bush block had higher bulk density values than the ct and nt tillage treatments.

Table 3.5. Bulk density (BD) values for six depth zones in the Rotgut trial sampled in 1996

Sample zone (cm)	BD g/cm^3
0 - 5	1.448 a
5 - 15	1.638 c
15 - 30	1.596 c
30 - 60	1.548 bc
60 - 90	1.513 b
90 - 120	1.516 b
tHSD	0.0614

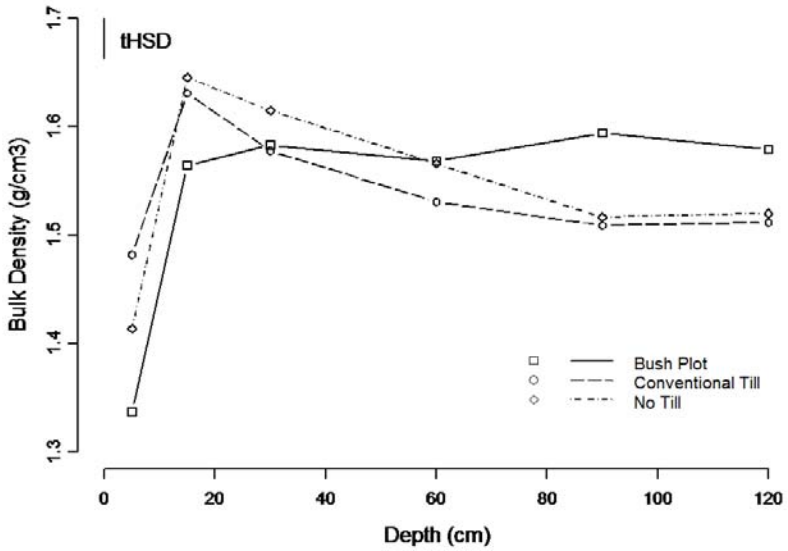

Figure 3.6. Bulk density (g/cm^3) values for six depth zones for the two tillage treatments in the Rotgut trial and an adjacent uncleared area which were both sampled in 1996, tHSD =0.0369

A comparison of the ox. C kg/m^3 values for the Rotgut treatments and the uncleared bush area gave a significant ($P < 0.0001$) interaction between the factors depth and group as shown in Figure 3.7. The rankings between treatments in the 0-5 cm sample zone were the same as that for the percentage ox. C values at this zone (Figure 3.5). But for the 5-15 cm zone, treatment rankings differed for the percentage

ox. C values at this depth. In this case, the bush values were lower than both ct treatments and the nt nil N treatment. The nt nil N was also higher than the nt mixed N at this depth. The bush area had higher values than all Rotgut treatments at both the 15-30 and 30-60 cm depths with no significant differences between Rotgut treatments at these depths. For the 60-90 and 90-120 cm depths, there were no significant differences between any treatments.

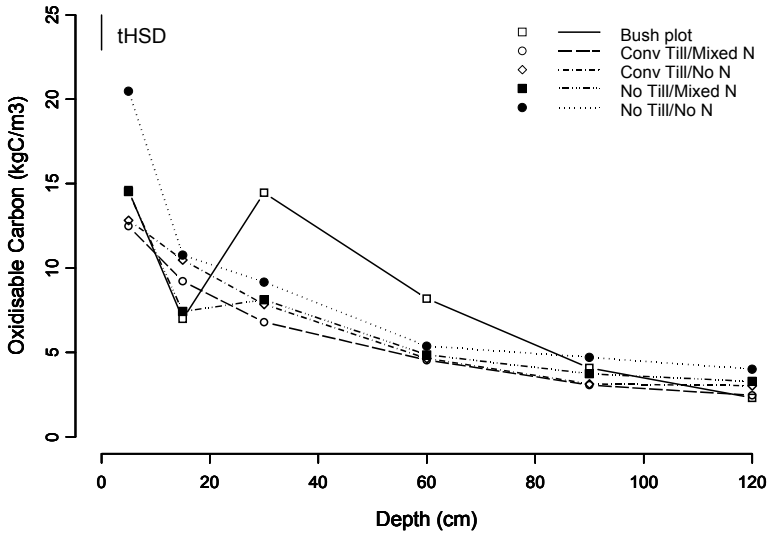

Figure 3.7. Oxidisable C kg/m^3 for four tillage (conventional or no till) by N (nil or mixed) Rotgut treatments and the bush area, tHSD = 2.0731

The total and average amount of ox. C in each sample zone on a ground surface-area (m^2) basis is presented in Table 3.6. The treatments had already been compared on a m^3 basis. The m^2 values allow the total ox. C content in the complete 1.2 m sample depth to be presented. The ranking for mean and total values were the same. Both bush and nt nil N had higher mean levels than the ct nil N and nt mix N. These were also higher than the ct nt mix N. The total weight of ox. C in the 1.2 m sample zone was greatest in the nt nil N and the bush block, which had similar values of 8.24 and 8.32 kg/m^2. Values for other treatments were considerably lower, ranging from 6.05 to 6.63 kg/m^2.

Table 3.6. Oxidisable C/m^2 values for each sample zone for the four Rotgut Tillage (conventional or no till) and N (nil or mixed) treatments and the bush area and total kg of oxidisable C across the complete 1.2 m depth, tHSD for mean 0.0881

Sample zone	Bush	ct nil N	ct mix N	nt nil N	nt mix N
Mean kg C/m^2	1.387 c	1.105 b	1.001 a	1.374 c	1.103 b
Total kg C/m^2	8.323	6.632	6.049	8.242	6.620

3.2.3 pH comparisons

All pH values in this section refer to the pH H_2O method. The pH values did not differ significantly between tillage treatments for any of the three sample zones (0-5, 5-15 and 15-30 cm) (Table 3.7). But for each of the zones, there were highly significant year effects ($P < 0.001$). There was a significant decline in pH occurring as the trial progressed but values also increased for some years at some sample depths (Figure 3.8). Tillage

and year did not interact significantly, which meant that the pH effects were non-specific to either nt or ct treatment in any year.

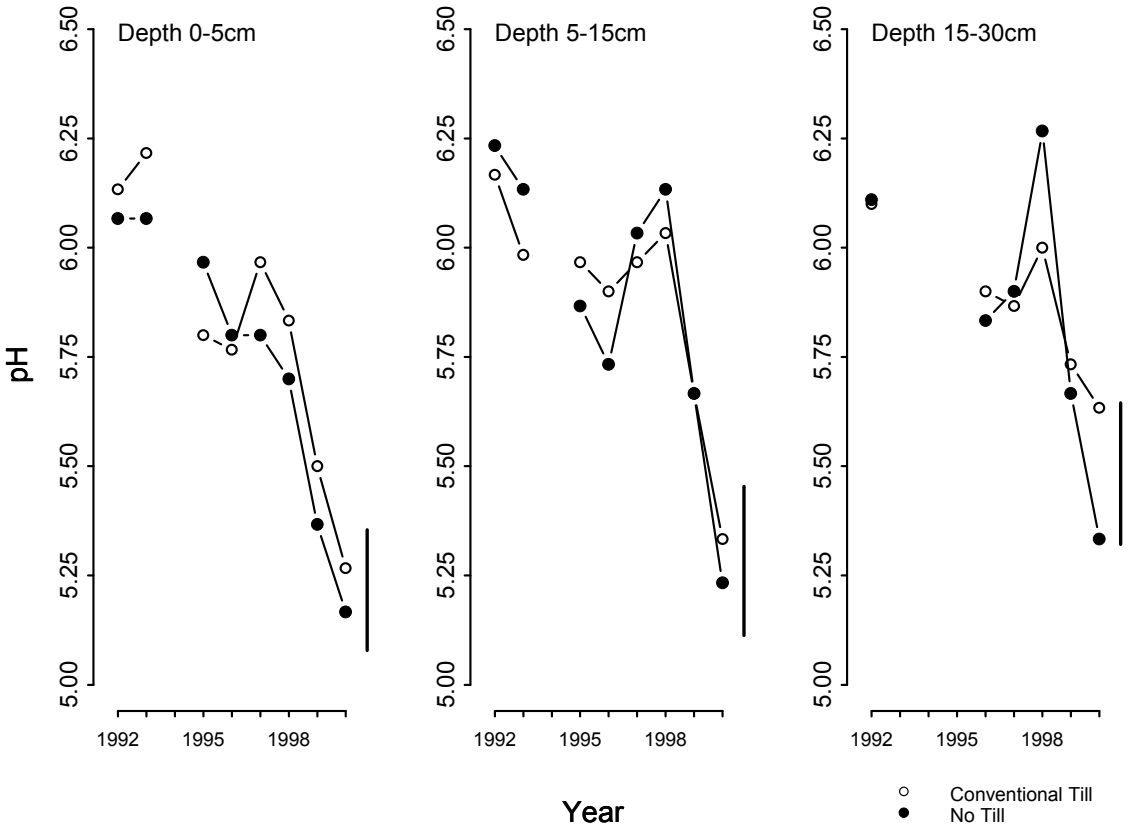

Figure 3.8. Values for pH H_2O for tillage treatments (conventional and no-till) for samples from the 0-5, 5-15 and 15-30 cm zones, error bars are Tukey's HSD values (0-5, 0.277, 5-15, 0.341 and 15-30 cm 0.323) for comparison of means between treatments and years

Table 3.7. Tillage treatment values for pH H_2O for tillage treatments no-till (nt) and conventional tillage (ct) for samples from the 0-5 (n = 8), 5-15 (n = 8) and 15-30 cm (n = 6) zones

	0-5 cm	**5-15 cm**	**15-30 cm**
nt	5.81	5.88	5.87
ct	5.74	5.88	5.85
P	> 0.05	> 0.05	> 0.05
HSD	0.598	0.742	0.323

For the pH main effect for the 0-5 cm zone, large and significant declines in pH values occurred between successive sampling years for the years 1998 to 1999 and 1999 to 2000. There was also a significant decline between non-successive sampling years for the period of 1992 to 1995 (Figure 3.9). No significant increases in pH for the 0-5 cm zone occurred. For the 5-15 cm zone, large and significant declines in pH values also occurred between successive sampling years for the years 1998 to 1999 and 1999 to 2000. There was also a significant decline between non-successive sampling years for the period of 1992 to 1995

and 1992 to 1996. A significant increase between non-successive sampling years also occurred from 1996 to 1998.

There were fewer sampling years for the 15-30 cm zone. Large significant declines in pH values occurred between successive sampling years for the 1998 to 1999 and the 1999 to 2000 years. For this depth, there was no significant change in pH between four samples collected from 1992 through to 1998.

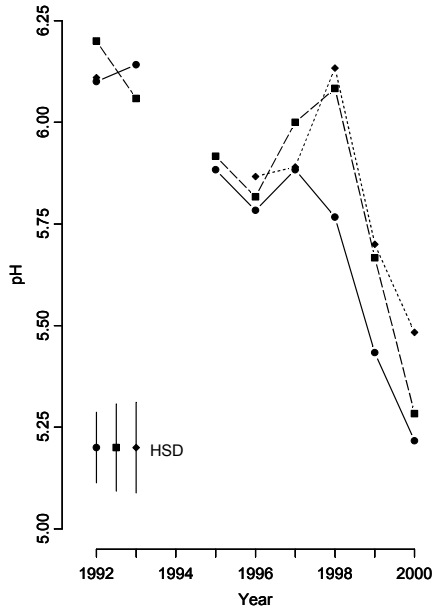

Figure 3.9. Soil pH means for years within each depth profile (circles 0-5 cm, squares 5-15 cm, diamonds 15-30 cm), Tukey's HSD values (HSD) are for means within each depth profile, HSD values are 0-5 cm, 0.174, 5-15 cm, 0.214 and 15-30 cm, 0.223.

1996 urea fertiliser effects on pH

For the 1996 samples, there were separate collections from areas with nil additional N (nil N) and split plots that had 70 and 140 kg/ha of urea applied (mixed N). The 1996 data presented in Figures 3.7 and 3.8 is from mixed samples from the 70 and 140 kg/ha areas.

There were no significant tillage effects but there were significant depth ($P < 0.05$) and N treatment ($P < 0.001$) effects. There were no significant interactions between any factors. For the depth effect ($F = 3.04$), the soil pH in the 0-5, 5-15 and 15-30 cm zones was significantly lower than in the 60-90 cm zone (Table 3.8).

Table 3.8. Soil pH by depth for 1996 samples, tHSD = 0.1921

Depth (cm)	pH
0-5	5.900 a
5-15	5.967 a
15-30	5.967 a
30-60	6.017 ab
60-90	6.192 b
90-120	6.075 ab

Separate from the depth effect was the greater (F = 56.90) effect of N treatments on pH. Samples from the nil N treatment had a significantly higher pH at 6.20 than samples from the mixed N treatment, which had a lower pH of 5.84 (Table 3.9). Thus the additional urea applications were associated with a decrease in pH of about 0.36 units.

Table 3-9. Soil pH by N treatment for 1996 samples, tHSD = 0.121

N treatment	pH
Nil additional N	6.20
Mixed N	5.84

pH in Rotgut plots in comparison with adjacent uncleared bush

A group based ANOVA comparison of the pH from the three plots of each Rotgut treatment with the three sample areas in the bush indicated a significant ($P < 0.001$) difference in soil pH between groups (Table 3.10). Both the nt and ct mixed N treatments had the lowest pH values (5.806 and 5.872, respectively). Both of these values were significantly lower than that of the bush (6.278), the nt nil N (6.250) and the ct nil N (6.150); pH values between other treatments did not differ significantly. There was no significant interaction between group and depth (data not presented).

Table 3.10. Soil pH values for samples from an uncleared bush area and samples from the Rotgut trial for treatment combination of no-tillage (nt), conventional tillage (ct), nil additional N (nil N) and additional N (mixed N), tHSD = 0.2306

Treatment	pH
uncleared bush	6.278 b
nt nil N	6.250 b
nt mixed N	5.806 a
ct nil N	6.150 b
ct mixed N	5.872 a

4 SYSTEMS TRIAL

4.1 INTRODUCTION

The Ley Farming Systems Project (commonly referred to as the Systems trial) was initiated in the 1994-95 season to evaluate a ley based farming rotation system for use in the semi-arid tropics of the NT. Ley farming is the rotation that makes use of pastures in rotation with crops. The Systems trial was large and sought to successfully integrate cropping, pasture and cattle production. The broad objectives were to assess the relative crop, pasture and livestock components in terms of productivity and economic returns, and jointly in terms of a total system.

Work has shown the importance of rotations for improving yields and profitability, especially where particular sequences can also reduce weed and pathogen management inputs, this is important for low-input systems and may affect long-term farm profitability in Australia (Lawes and Renton 2010). Developing successful ley-based farming systems in the semi-arid tropics is, however, regarded as challenging due to a number of common problems, such as grass dominance of the pasture, very rapid legume residue decomposition and loss of mineral N that limit the benefits of legumes to the system and a lack of sufficient crop and/or pasture residues in extreme seasons to assist with no-till drilling methods (Jones et al. 1991; McCown 1996).

This trial ran from the 1994-95 season to the 2003-04 season, but soil samples were no longer analysed after May 2001 due to the Berrimah Soils Laboratory introducing service fees. This section of the report focuses on the period from 1994-95 to the 2000-2001 season where soil results are available.

Overview of trial and soil quality report focus

The trial was based on comparing ley rotations initiated with either a ley pasture or crop. Within the ley pasture or grain crop initiated rotations, there were also additional treatments. The additional treatments were the ley pasture composition (pure legume or a grass-legume pasture) and dry season stocking rate (low, medium or high). A separate area of continuous sorghum cropping was used for a comparison with the ley rotations.

A large number of soil results were collected from the trial; however, for different periods of the trial, different depth samples were collected which limited the ability to make comparisons among treatments for all years of data. We selected periods when same depth samples were collected in order to examine this data for the effects of rotation, pasture species and grazing treatments on soil ox. C concentrations and pH. Where possible, factors identified as affecting soil pH or soil C concentrations in mixed cropping and ley pasture studies in semi-arid environments from other Australian or international studies were investigated (Jones et al. 1991; McCown 1996; Dalal and Carter 2000).

Site history

The Systems trial was established in what had been Paddocks 56 and 57 at DDRF on a soil that has generally been described in the soil family ‘Blain’ (Plate 1). Under Australian Soil Classification systems this family has been described as Deep Red Magnesic Kandosols (Hill et al. 2011). A Blain soil was selected as it is one of the most common soil types used for agriculture in the region. Unfortunately, no soil description has been carried out at the site with the exception of an NRETAS land form assessment (OLLOO 25) in the middle of field 57 described on 14/10/1981 (NRETAS 2011).

Prior to the establishment of this trial, the area was open woodland with some aerially-sown stylo. The woodland was progressively cleared, prepared and sown to each phase as described below.

Field 56 was uncleared bush until chain clearing in 1993. Between mid-1994 and October 1994 the area was stick-raked, pin-wheeled and the windrows were burnt. Around November 1994 the area was cultivated using off-set discs and a chisel plough and pin-wheeled three times. In early December 1994, the area was harrowed prior to planting with bull-rush millet. In January 1995, the area was sprayed off and the first ley pasture was initiated. Rotation wet season leys were sown from mid-January to early February 1995. Fourteen hectares of field 56 and 14 hectares of field 57 were used for Phase 2 with trees chain-cleared in 1993. Between mid-1994 and October 1994, this area was also stick-raked, pin-wheeled and the windrows were burnt. Fifteen hectares of field 57 had trees removed in 1994 and was then stick-raked, pin-wheeled and cleared vegetation burnt in early 1995. Both areas were then sown with grain sorghum on 30/12/1995 for the first season treatment for the first grain crop pasture initiated rotation. For the area used for the second ley pasture initiated rotation, 18 hectares of Field 57 were chain-cleared in 1993. The area was stick-raked, pin-wheeled, the windrows were burnt and the area was chisel-ploughed between July and October 1995. The area was fertilised with 200 kg/ha of 0-10-20-5 (0-10-19.5-5.1), and then offset ploughed again to incorporate the fertiliser. Grain sorghum was planted in the area on 18/12/1995.

4.2 METHODS

Design

The trial was based on three unreplicated ley pasture rotations (ley pasture or grain crop initiated), each of which was 28 hectares. Each ley pasture rotation had a ley pasture species treatment (pure legume or a grass-legume pasture) consisting of two main plots, each of which was 14 hectares. Each main plot had three split plot dry season stocking rate treatments (low, medium or high). There were a 6-hectare and two 4-hectare split plots for each main plot. These treatments and an additional reference continuous cropping treatment are described in more detail below.

Crop rotation: The basic unit of the ley rotation was two years of grazed pasture (ley pastures) and a single wet season grain crop in which the crop residues were grazed in the dry season. The rotation treatments differed with the first crop being a ley pasture or a grain crop. Table 4.1 presents an overview of the trial treatments. The ley pasture species treatment was a mixed pasture (MP) of Cavalcade and sabi grass, or a Cavalcade only based pasture. The grain crop in the rotation was grain sorghum (*Sorghum bicolor*).

Table 4.1. Summary of the Systems trial with ley pasture or grain crop initiated rotation treatments, pasture species treatments of mixed pasture or Cavalcade (Cav), the grazing treatments (L, low, M, medium, H, high) and a continuous grain sorghum treatment

Initial crop	**Ley pasture**	**Ley pasture**	**Grain crop 1**	**Grain crop 1**	**Grain crop 2**	**Grain crop 2**	**Cont. grain sorghum**
Pasture	**Mixed pasture**	**Cav**	**Mixed pasture**	**Cav**	**Cav- mixed pasture**	**Mixed pasture-Cav**	**Field 19**
Grazing	**L-M-H**	**L-M-H**	**L-M-H**	**L-M-H**	**L-M-H**	**L-M-H**	
1994/95	Mixed pasture 1st yr	Cav Pasture 1st yr	Sorghum	Sorghum	Cleared	Cleared	Cleared
1995/96	Mixed pasture 2nd yr	Cav pasture 2nd yr	Mixed pasture 1st yr	Cav pasture 1st yr	Sorghum	Sorghum	Sorghum
1996/97	Sorghum	Sorghum	Mixed pasture 2nd yr	Cav pasture 2nd yr	Cav pasture 1st yr	Mixed pasture 1st yr sown	Sorghum
1997/98	Mixed pasture 1st yr	Cav. pasture 1st yr	Sorghum	Sorghum	Cav pasture 2nd yr	Mixed pasture 2nd yr	Sorghum
1998/99	Mixed pasture 2nd yr	Cav pasture 2nd yr	Mixed pasture 1st yr	Cav pasture 1st yr	Sorghum	Sorghum	Sorghum
1999/00	Sorghum	Sorghum	Mixed pasture 2nd yr	Cav pasture 2nd yr	Mixed pasture 1st yr	Cav pasture 1st yr	Sorghum
2000/01	Mixed pasture 1st yr	Cav pasture 1st yr	Sorghum	Sorghum	Mixed pasture 2nd yr	Cav pasture 2nd yr	Sorghum

Although there were two grain crop initiated rotations (numbers 1 and 2, initiated in 1994 and 1995, respectively), they differed in that the 1995 initiated rotation was established on recently-cleared land. The 1995 grain crop initiated rotation 2 also differed in that the same ley pasture species were not repeated in the second rotation. The rotation treatment of GS-Cav-Cav was followed by GS-MP-MP, and the GS-MP-MP was followed by GS-Cav-Cav.

For the ley pasture initiated rotation (first season, 1994-95) and the grain crop initiated rotation 1 (first season, 1994-95), two complete rotations (1994-95 to 1996-97 and 1997-98 to 1999-00) were completed. A third rotation was started in the 2000-01 season but this was not completed. For the grain crop initiated rotation 2 (first season, 1995-96), as there were two different pastures in the complete rotation treatment, a single rotation was six years long as opposed to three years for the other rotation treatments. The 2000-01 season of the experiment saw the completion of one rotation for the second grain crop initiated rotation.

For the continuous grain sorghum treatment (Field 19) the first sorghum crop was planted the same time as the second grain crop initiated rotation using the same fertiliser and cultivation in December 1995. Part of the paddock had a replicated conventional till (ct)/ no-till (nt) treatment for the first two wet seasons (1995-96 and 1996-97). A larger area was then used for the tillage treatments from 1997-98 seasons onwards (4 hectares in total). This rotation had a light grazing rate of one animal/ha) over the dry season.

Grazing treatments: Three grazing treatments were established as split plots in each of the ley pasture treatments (Table 4.1). The treatments were low, medium and high stocking densities of one, two and three animals/ha, respectively. Grazing ran over the dry season typically with weaners weighing about 150 kg each being introduced in August (Lemcke et al. 1997).

Management inputs: Direct drilling methods were used for all crops. Following the initial three year rotation, the ley pastures successfully re-established after the sorghum crop and did not require sowing. Herbicide inputs on the trial area were often substantial due to problems with both grass and broadleaf weeds.

Although sorghum was drilled each season with no-till practices, the whole of the second grain crop initiated rotation area, including Field 19, was ploughed due to problems with high levels of vegetative matter after the first season's crop of sorghum (1995-96), to allow the drilling of the 1996-97 ley pastures.

Table 4.2 shows a record of fertiliser inputs to the rotations. The ley pastures were typically managed with no fertiliser N, but with single super, which was commonly applied. The application rates in each of the first two seasons (~200 kg) of single super to ley were higher than those used in the later seasons (~50 kg). The sorghum crops in each phase received the most fertiliser inputs including nitrogenous fertilisers most commonly as urea. Total kg/ha for each season are provided. Typically, most fertiliser was applied each season at drilling in December with later top dressings in January with additional N for the sorghum crops. From the 1998-99 season onwards phases with sorghum crops in these seasons had 19.13.0.9 applied. This was considered to be in the form of diammonium phosphate (DAP, $(NH_4)_2HPO_4$) blended with sulphate of ammonia (P. Hausler, pers.comm.). In addition, there was some application of muriate of potash (MOP, potassium chloride).

For the continuous sorghum control in field 19 fertiliser inputs were 1995-96, 0.10.20.5 + trace elements (te) 200 kg, urea 50 kg; 1996-97, 0.11.20.6 + te 206 kg, urea 60 kg; 1997-98, 0.14.0.17 + te 150 kg, urea 230 kg; 1998-99, 19.13.0.10 200 kg, MOP 75 kg; 1999-2000, MOP 50 kg, 0.14.0.10 120 kg, 19.13.0.9 200 kg, urea 100 kg; 2000-01 ,urea 190 kg, 19.13.0.9. One area of field 19 from May 1999 was placed under conventional cultivation and drilling as a comparison with no-tillage drill methods used in the rest of this field.

Table 4.2. Fertiliser inputs for the three rotations over seven seasons with the month of application. Application values for NPKS fertilisers are indicated with values as for pasture initiated, November 1994 with an application of 0.7.13.8, te = trace elements, MOP = muriate of potash (potassium chloride), for each application rates are kg/ha.

Season	Date	Pasture initiated	Applications	Grain initiated 1	Applications	Grain initiated 2	Applications
94-95	Nov 94	Leys	0.7.13.8 + te, 130 kg	Sorghum	0.7.13.8 + te, 130 kg	-	-
	Jan 95	Leys	0.11.20.6 + te, 83 kg	Sorghum	Urea, 95 kg	-	-
95-96	Nov 95	Leys	0.10.20.5 + te, 210 kg	Leys	0.10.20.5 + te, 200 kg	Sorghum	0.10.20.5 + te, 200 kg
	Dec 95					Sorghum	Urea, 50 kg
	Jan 96						Urea, 100 kg
96-97	Dec 96	Sorghum	0.11.20.6 + te, 180-233 kg 0.18.0.10, 32 kg, Urea, 0 to 240 kg*	Leys	0.11.20.6 + te, 196 kg	Sorghum	0.11.20.6 + te, 206 kg
97-98	Dec 97	Leys	0.16.0.20, 50 kg	Sorghum	0.11.20.6 + te, 200 kg	Leys	0.16.0.20, 50 kg
	Jan 98			Sorghum	Urea, 90 kg		
98-99	Dec 98	Leys	0.16.0.20, 50 kg	Leys	0.14.0.18, 50 kg	Sorghum	19.13.0.9, 200 kg
						Sorghum	Urea, 100 kg
99-00	Dec 99	Sorghum	MOP, 110 kg 19.13.0.9, 185 kg	Leys	0.14.0.18, 50 kg	Leys	0.14.0.18, 50 kg
	Jan 99	Sorghum	Urea, 100 kg				
00-01	Dec 00	Leys	0.14.0.18, 50 kg	Sorghum	MOP, 50 kg 19.13.0.9, 180 kg	Leys	0.14.0.18, 50 kg
	Jan 01			Sorghum	Urea, 90 kg		

* Indicates that split plot fertiliser treatments were used for that application.

Soil sampling methods: Soil samples were collected separately in each grazing split-plot treatment with a 34 mm diameter corer. Soil samples were taken to coincide with the vegetation sampling, which occurred approximately at the end of the dry season/beginning of the wet season (November), and the end of the wet/beginning of the dry (May). From 1996 onwards, samples were usually taken at six sites per grazing treatment. For some sampling dates, all six samples were pooled for analysis. They are described as pooled samples. Samples from sites 1 and 6, sites 2 and 5, and sites 3 and 4 were separately bulked to provide three samples for analysis. These sites respectively corresponded to top, middle, and bottom of the fields. These samples are described as area subsamples. Over the first four years of the trial, samples were collected from differing depths but from 1998 onwards, samples were collected from two depths only, 0-15 cm and 15-30 cm. Table 4.3 provides an example of the soil samples and available analyses from field 1 in the pasture initiated rotation treatment. Sampling sometimes differed between different rotation treatments. Fields in the grain crop initiated rotation treatments were comparatively less regularly sampled than those of the pasture initiated treatment during the first few years of the trial from 1996 to 1997. Field 19 mostly had three samples collected at each sampling date and depth, up until the establishment of a conventional tillage treatment area in 1999. Following the establishment of the conventional tillage treatment, three separate samples were collected from the two tillage treatment areas.

Samples were air-dried, ground and sieved (1.2 mm aperture sieve) before analysis at the DPIF soils laboratory in Darwin.

Table 4.3. Soil samples from field 1 (treatment: mixed pasture initiated, medium stock grazing rate) listed by sample month, crop at sampling, depth of samples and 'yes' if area sub samples were kept separate

Sample date	Crop stage	Depth (cm)	Sub sample
May 1995	Mixed pasture, year 1	0-15	yes 1/ha*
February 1996	Mixed pasture, year 2	0-5, 5-15, 15-30, 30-60, 60-90, 90-120	none
March 1996	Mixed pasture, year 2	0-20	none
November 1996	Mixed pasture, year 2, pre-sowing sorghum	0-15, 15-30	none
May 1997	Post-harvest sorghum, pasture established?	0-5, 5-15, 15-30,	none
October 1997	Mixed pasture, year 1	0-10, 10-30	yes
May 1998	Mixed pasture, year 1	0-15, 15-30	none
November 1998	Mixed pasture, year 2	0-15, 15-30	none
May 1999	Mixed pasture, year 2	0-15, 15-30	yes
October 1999	Mixed pasture, year 2, pre-sowing sorghum	0-15, 15-30	yes
May 2000	Post-harvest sorghum, pasture established	0-15, 15-30	yes
December 2000	Mixed pasture, year 1	0-15, 15-30	yes
May 2001	Mixed pasture, year 2	0-15, 15-30	yes

* For the 1995 sample ~1 core was collected per/ha in each split plot.

Analysis

Analysis was based on data summaries, comparisons of mean values from plots over time and/or between treatments. Although fields were sampled on a seasonal basis, repeated measures analysis (ANOVA) was not considered in these comparisons due to the absence of proper replication (methods varied with time and the fashion in which depth profiles were sampled) of rotation treatments. Therefore, data from different seasons from the same fields were treated as being independent (although they are unlikely to have been wholly independent).

Firstly, comparisons focussed on selected rotation treatments or sampling occasions that had enough sampling effort to allow single point-in-time treatment comparisons. These included dates when a large

number of depths were sampled (Part A). Secondly, comparisons focused on results for which a series consecutive sample dates with the same depth were available (Part B). Thirdly, time effects were examined using linear regression (Part C).

For both Part A and B, due to the inability to adequately separate the effects of grazing treatments from rotation or ley pasture species treatment effects and lack of replication to allow the effects of multiple factors to be isolated, separate analyses for grazing and rotation treatment effects were made. The grazing treatments were established on a split-plot basis but the structure of the general linear models (GLM or ANOVA) did not account for the reduced degrees of freedom of a split-plot design. As such, the models used in this way will have tended to overestimate the significance of any grazing treatment effects. This was acknowledged as a limitation, but this approach was used as it provided a simplistic and risk adverse method to identifying any grazing effects. If grazing effects were identified, more appropriate analyses could be used to explore these further. For all comparisons, any plots with multiple samples were averaged to provide single values per plot for comparison. As an example, Table 4.4 presents the number of sample analyses available by sample date, rotation and ley pasture species treatments for 0-15 cm and 15-30 cm samples, from which single means were calculated for use in analyses of ley treatments and for time effects.

Table 4.4. A summary of the number of pH and oxidisable C sample analyses available for the mixed pasture (MP) and Cavalcade (Cav) species treatments in the pasture initiated rotation and the first and second grain crop initiated rotations for 0-15 cm and 15-30 cm samples by sample date

0-15 cm

Pasture initiated	**Ley**	**Ley**	**Grain crop initiated 1**	**Ley**	**Ley**	**Grain crop initiated 2**	**Ley**	**Ley**
	Cav	**MP**		**Cav**	**MP**		**Cav/MP**	**MP/Cav**
Sample date			Sample date			Sample date		
9/05/1995	3	3	-	-	-	-	-	-
19/11/1996	3	3	6/08/1996	3	3	6/08/1996	3	3
1/05/1998	9	7	1/05/1998	9	9	1/05/1998	9	9
1/11/1998	9	7	1/11/1998	9	7	1/11/1998	9	9
1/05/1999	9	9	1/05/1999	9	9	1/05/1999	9	9
1/10/1999	9	9	1/10/1999	9	9	1/10/1999	9	9
1/05/2000	9	9	1/05/2000	9	9	1/05/2000	9	9
1/12/2000	9	9	1/12/2000	9	9	1/12/2000	9	9
1/05/2001	9	9	1/05/2001	9	9	1/05/2001	9	9

15-30 cm

Pasture initiated	**Ley**	**Ley**	**Grain crop initiated 1**	**Ley**	**Ley**	**Grain crop initiated 2**	**Ley**	**Ley**
	Cav	**MP**		**Cav**	**MP**		**Cav/MP**	**MP/Cav**
Sample date			Sample date			Sample date		
1/02/1996	3	3	-	-	-	-	-	-
19/11/1996	3	3	-	-	-	-	-	-
15/05/1997	3	3	7/05/1997	3	3	1/05/1997	3	3
1/05/1998	9	7	1/05/1998	9	9	1/05/1998	9	9
1/11/1998	9	7	1/11/1998	9	7	1/11/1998	9	9
1/05/1999	9	9	1/05/1999	9	9	1/05/1999	9	9
1/10/1999	9	9	1/10/1999	9	9	1/10/1999	9	9
1/05/2000	9	9	1/05/2000	9	9	1/05/2000	9	9
1/12/2000	9	9	1/12/2000	9	9	1/12/2000	9	9
1/05/2001	9	9	1/05/2001	9	9	1/05/2001	9	9

Part A: The comparison of results from a sufficient number of depths was needed to provide more than 16 degrees of freedom (df). On this basis, comparisons were made of data from the pasture initiated rotation in February 1996 when six depth zones were sampled. Four GLMs were used: GLM 1 and 2 for pH and ox. C with the factors depth, grazing and depth*grazing; then GLM 3 and 4 for pH and ox. C of depth, pasture species and depth*pasture species.

Part B: For the results where samples had been collected consecutively using the same sample depths as was carried out from May 1998 to May 2001 for all three rotation treatments the data was plotted separately for the ley and grazing treatments. These plots are presented in Appendix 6. Due to the grazing treatments being established as split plots and the rotation treatments not being replicated, interactions between ley and grazing treatments could only be compared by comparing individual replicates of grazing treatments. This was not attempted. Instead, the plotted averages of grazing and ley pasture treatments were used as a guide for selecting factors and interactions for examination.

To enable the rotation treatments to be compared, a sample series from November 1998 to May 2001, which provided a balanced data set of consecutive samples from the same sample depth, was used (Table 4.5). However, as the rotation treatments differed in the initiation sequence order and the design was not factorial, the ley pasture species and grazing intensity treatments between these two rotations (or the grain crop 2 initiated rotation) are not true replicates. Rotation effects or interactions including rotation provided separation of the different rotation treatments and their associated treatments. Therefore, only significant interactions of ley pasture species or grazing treatments with the rotation treatments or rotation main effects were regarded as useful for discussion. The effects of grazing treatments were examined with this three rotation data set.

Table 4.5. Selected sample series for factor comparisons showing the crop stages of each of rotation treatments in the three rotation treatments

Sample date	Pasture initiated rotation	Grain crop initiated rotation 1	Grain crop initiated rotation 2
1/11/1998	Ley pasture, year 2	Ley pasture, year 1	Pre-sow sorghum
1/05/1999	Ley pasture, year 2	Ley pasture, year 1	Post sorghum
1/10/1999	Pre-sow sorghum	Ley pasture, year 2	Ley pasture, year 1
1/05/2000	Post sorghum	Ley pasture, year 2	Ley pasture, year 1
1/12/2000	Ley pasture, year 1	Pre-sow sorghum	Ley pasture, year 2
1/05/2001	Ley pasture, year 1	Post sorghum	Ley pasture, year 2

The differing ley pasture species treatments of grain crop initiated rotation 2 where the pasture species treatments were swapped in the 1999-00 season from the prior species treatments (Tables 4.1 and 4.2) did not provide a balanced structure for comparing the ley pasture treatments. Balanced comparisons could only be made between the pasture initiated rotation and the grain initiated rotation 1. A subset of the above data containing only phases 1 and 2 was used to examine ley pasture treatment effects. For this subset grazing effects were not re-examined.

Part C: Linear regressions of the cumulative day count for each sample date against the dependant variable (soil pH or ox. C) for data from the same sample depths were completed. As phase and ley pasture treatments often interacted significantly with sample date (Figures 4.1, 4.2, 4.3 and 4.4), the grazing treatment was not significant. Separate analyses were made for the three phases and their ley pasture treatments with a comparison with the continuously-cropped sorghum control included.

4.3 RESULTS

4.3.1 Weather during the sample period

The long-term average rainfall during the four months of peak rainfall (December to April inclusive, 1968-2011) was 1067 mm. It was close to the average rainfall (1178.6 mm) for the period of the trial discussed in this report (Table 4.6). The differences between individual season's rains over this trial period have already been discussed in the Species and Rotgut sections of this report.

Plots in both grain crop initiated rotations generally had some flooding on average every second wet season. Flooding of most paddocks occurred in the wet season of 1998, including all of grain crop initiated rotation 1 and most of grain crop initiated rotation 2. The most affected paddocks were two split plots (fields 10 and 11) where water stayed above the soil for the longest time and was noted as affecting crop and pasture growth.

Table 4.6. Rainfall recorded at DDRF for the seven season of the Systems trial discussed in this report for the long-term average wettest months (1 December to 30 April), annual seasonal rainfall (1 July to 30 June) and the December to April rainfall as percentage of annual seasonal rain, including mean, standard deviation, coefficients of variation (CV) and long term average rainfall

	Dec.-Apr.	June-July	% wet of annual
Average for 1968-2011	1067.4	1182.7	90.3
1994-1995	782.9	849.6	92.1
1995-1996	965.1	1096.7	88.0
1996-1997	1064.2	1269.2	83.8
1997-1998	1595.6	1695.8	94.1
1998-1999	1472.3	1590.6	92.6
1999-2000	1289.5	1449.4	89.0
2000-2001	1080.4	1192.8	90.6
Mean	1178.6	1306.3	90.0
Std. dev.	287.9	294.3	3.4
CV	0.24	0.23	0.04

4.3.2 Part A: Effects in the pasture initiated rotation only

Pasture initiated rotation, season 2: The six fields in this rotation had six depths sampled in the wet season of February 1996 as presented in Table 4.7. This was the second season of the ley pasture (sown 1994-95 season) in this rotation treatment. Analyses for the first models (df = 18) including grazing, showed that grazing had no significant effect on soil pH (depth P = 0.007, grazing P = 0.249 and depth*grazing, P > 0.05) or ox. C concentrations (depth P <0.0001, grazing P = 0.6281 and depth*grazing, P > 0.05).

In the analyses, including pasture species (df = 24) for soil pH, both depth (P = 0.0006) and pasture species (P = 0.0118) had significant effects, with no significant interactions. For the depth effect, soil pH significantly declined from the 5-15 cm sample depth with increasing depth with the exception of the 0-5 cm depth (Table 4.7). Samples from the bottom two depths had significantly lower values than those from the 5-15 cm and 15-30 cm depths. For the pasture species effect, Cavalcade had a lower pH than the mixed pasture treatment by approximately 0.25 units (Table 4.8).

In the analyses, including pasture species (df = 24) for ox. C concentrations, both depth (P < 0.001) and pasture species (P = 0.0275) had significant effects, with no significant interactions. There was a consistent and significant decline in ox. C concentrations with increasing soil depth, particularly for samples from the 15-30 cm and deeper zones in comparison with the top 0-5 cm (Tables 4-7). The mixed pasture had higher ox. C concentrations than the Cavalcade treatment (Table 4.8).

Table 4.7. Soil pH and oxidisable C (ox. C) concentrations for six depths of samples collected in February 1996 from the pasture initiated rotation treatment, df = 24

Depth (cm)	pH	ox. C
0-5	7.03 ab	0.722 c
5-15	7.32 b	0.617 bc
15-30	7.22 b	0.558 b
30-60	6.98 ab	0.372 a
60-90	6.57 a	0.242 a
90-120	6.50a	0.250 a
SEM	0.132	0.0348
HSD	0.579	0.153

Table 4.8. Soil pH and oxidisable C (ox. C) concentrations in the pasture treatments of mixed pasture (MP) and Cavalcade (Cav) in February 1996 from the pasture initiated rotation treatment, df = 24

Pasture	pH	Ox. C
MP	7.08	0.493
Cav	6.79	0.427
SEM	0.076	0.0201
HSD	0.223	0.0590

Pasture initiated rotation, effects from season 2 to 3: A comparison was made between time effects in the pasture initiated rotation treatment between the second year of ley pastures (wet season February 1996, 1995-96 season) and samples after the grain sorghum crop had been harvested in the following season (dry season May 1997, 1996-97 season) for three sample depths. The factors sample depth, time (1996 or 1997) and grazing or ley pasture species with grazing or ley pasture species*time and grazing or ley pasture species*depth were investigated.

For the pH model, including grazing, both time (P = 0.003) and grazing (P = 0.013) had significant effects, with no significant interactions between factors. For time effects, the pH decreased from the 1996 sample with a pH of 7.19 to 6.60 in the 1997 sample (SEM 0.097). The significant grazing effect was between the pH of the medium density grazing treatment, 7.19, and the high grazing treatment, which had a value of 6.66 (SEM 0.119, HSD 0.421). The low grazing treatment had an intermediate value of 6.83. For the ox. C model including grazing, both time (P = 0.0017) and sample depth (P < 0.001) had significant effects; grazing had no significant main effect and did not interact significantly.

For the pH model, including ley pasture species, time (P = 0.003) had a significant effect and ley pasture species interacted significantly with time (P = 0.013), but there was no significant main effect for ley pasture species. The pH time effects were reported above. In the interaction, both ley pastures had declines in pH between the sample dates, but only for the MP treatment was this significant (Table 4.9).

Table 4.9. Soil pH values from the ley pasture treatments of mixed pasture (MP) and Cavalcade (Cav) samples collected in February 1996 and May 1997 from the pasture initiated rotation treatment, df = 28

Depth (cm)	Time	pH
Cav	1996	6.94 abc
Cav	1997	6.71 ab
MP	1996	7.43 c
MP	1997	6.49 a
SEM		0.133
HSD		0.516

For the ox. C model, including ley pasture species, both time (P = 0.0005) and depth (P < 0.001) had significant effects (Table 4.10). Ley pasture species was not a significant factor and there were no significant interactions. The ox. C value was lower at the second sample date and significantly less ox. C was detected with increasing sample depth.

Table 4.10. Soil oxidisable C (ox. C) concentrations for February 1996 and May 1997 and for three sample depths from the pasture initiated rotation treatment, df = 28

Time	ox. C (%)	Depth (cm)	ox. C (%)
1996	0.632	0-5	0.696 c
1997	0.494	5-15	0.583 b
		15-30	0.412 a
SEM	0.0247		0.0302
HSD	0.0719		0.1060

4.3.3 Part B: Consecutive samples 1998 to 2001, rotation comparisons

Plots of May 1998 to May 2001: Potential factors for analyses were selected for the rotation treatments from plots of results of the ley and grazing treatments (Appendix 6).

The plots of the grazing treatments in the three phases did not show clear differences between the three grazing densities except for a period in the pasture-initiated rotation when the low grazing treatment from May 1998 to November 2000 had lower pH values at both sample depths. This indicated a possible grazing*date*depth interaction. The pH values for the grain crop-initiated rotation 1 differed from those in the other two rotations with a general decline apparent over time. For the ox. C plots, there were some non-consecutive sample dates where a single treatment at a single date had higher or lower values than the other two treatments, but generally these results did not indicate clear or consistent ox. C grazing treatment effects.

For the ley treatment plots of soil pH, mean values showed that both rotation and rotation*time interactions may be important with the pH of grain crop-initiated rotation 1 in particular appearing to differ from the other two phases. In addition, pH appeared to decline with time in grain crop-initiated rotation 1. There was also some indication of rotation*time*ley pasture interactions; for example, in May 1998 in the pasture-initiated and grain crop-initiated rotation 1 the Cavalcade ley had a lower pH than the mixed pasture ley. For plots of ox. C values rotation also appeared important as for the grain crop-initiated rotation 2. Ox. C values were on average for both depths higher than those for the other rotations. Possible rotation*time, rotation*time*ley pasture and rotation*time*depth were also evident at a limited number of sample dates.

Factors affecting pH and ox. C values, rotation and grazing treatment comparisons: Using the data described above and listed in Table 4.5 for the three rotations, the effects of rotation on soil pH and ox. C concentrations were investigated. Separate analyses were carried out for the grazing and rotation effects. Any non-grazing rotation effects in the grazing model are not discussed.

For the grazing models, factors were grazing, date, sample depth, rotation, grazing*date, grazing*depth, grazing*rotation, grazing*rotation*sample date and grazing*rotation*depth (df = 57). For soil pH, grazing had no significant main effect (P = 0.0811) and did not significantly interact with any factor. The soil pH values for the three grazing treatments of low, medium and high intensities were 6.36, 6.48 and 6.43, respectively (SEM 0.0369). The pH values for the two sample depths in the three rotations are presented in Table 4.11. The ox. C concentrations had a similar result to that of soil pH, with grazing not providing a significant main effect (P = 0.7776) or significantly interacting with any factor. Soil ox. C values for the three grazing treatments of low, medium and high grazing rates were 0.465, 0.470 and 0.461%, respectively (SEM 0.0095). Ox. C values for the two sample depths in the three rotations are presented in Table 4.11.

Table 4.11. Soil a) pH (SEM 0.0852) and b) oxidisable C (ox. C, %) concentrations (SEM 0.0220) for the three rotation treatments (as listed in the table) for two sample depths

	Pasture initiated rotation			**Grain crop 1 initiated rotation**			**Grain crop 2 initiated rotation**		
Grazing intensity	low	med	high	low	med	high	low	med	high
Depth									
a) pH									
0-15 cm	6.41	6.63	6.51	6.21	6.26	6.23	6.32	6.40	6.44
15-30 cm	6.51	6.71	6.62	6.32	6.39	6.27	6.40	6.52	6.49
b) ox. C									
0-15 cm	0.570	0.568	0.606	0.589	0.589	0.576	0.664	0.664	0.616
15-30 cm	0.307	0.318	0.295	0.297	0.314	0.319	0.365	0.384	0.351

For the model separately, including rotation, the factors and interactions included were rotation, date, sample depth, rotation*date and rotation*depth (df = 15). Due to the limited degrees of freedom associated with the design of the trial, the three way interaction between rotation*depth*date was examined in a separate model, including the three sole factors and the three way interaction (df = 17).

For the pH model, sample date, depth and rotation were all significant factors and the interactions of sample date*rotation (P <0.001) and sample depth*rotation (P = 0.0094) were significant. The pH of soil from the 15-30 cm zone at 6.47 was higher than that from the 0-15 cm zone at 6.39 (SEM 0.0162, HSD 0.049). The pasture-initiated rotation (6.57) had a higher pH than the grain-initiated rotation 2 (6.42) and both of these rotations had a higher pH than the grain initiated rotation 1, which had the lowest pH at 6.28 (SEM 0.020, HSD 0.073). The pH model, including the rotation*depth*date interaction, was not significant (data not presented).

For the rotation by sample date interaction, the grain-initiated rotation 2 had a lower pH than the pasture-initiated rotation in May 1999 and again in December 2000, while the grain-initiated rotation 1 had a lower pH than both other rotations in May 2000 and 2001 but only differed from the grain-initiated rotation 1 in December 2000 (Figure 4.1). Significant increases in pH also occurred in the pasture-initiated rotation and the grain-initiated rotation 1 from mid to late 2000. In contrast, for this period no significant change occurred in the grain-initiated rotation 2.

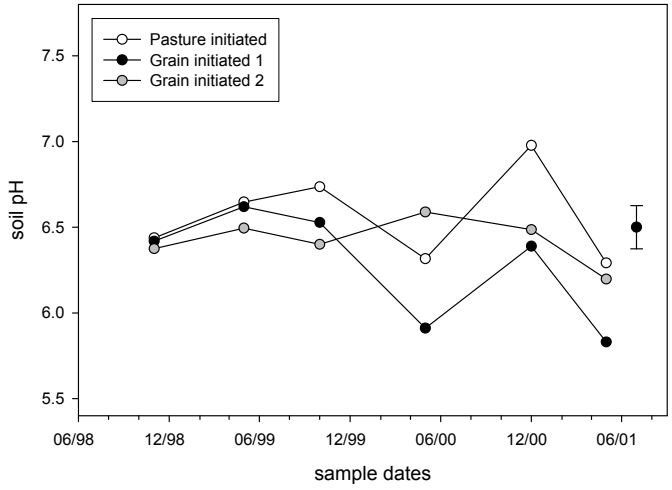

Figure 4.1. Soil pH values at six sample dates from 1998 to 2001 for the pasture, grain crop 1 and grain crop 2 initiated rotation treatments samples (SEM 0.049, HSD error bar 0.253)

The sample depth by rotation interaction was due to the pH of the pasture-initiated rotation and the grain crop-initiated rotation 1, not differing between their respective two sample depths. But for the grain crop-initiated rotation 2 the 15-30 cm depth had a higher pH than the 0-15 cm depth (Table 4.12). In addition, the pH at the 15-30 cm depth did not differ significantly between the pasture-initiated rotation and the grain crop-initiated rotation 2. But for the 0-15 cm samples from these phases, the pasture- initiated rotation had a higher pH than the grain crop-initiated rotation 2.

Table 4.12. Soil pH values for the three rotation treatments (as listed) and two soil sample depths, df = 15, SEM 0.028, HSD 0.129

Sample depth (cm)	0-15	15-30
Rotation		
Pasture-initiated rotation	6.57 b	6.56 b
Grain crop-initiated rotation 1	6.24 a	6.32 a
Grain crop-initiated rotation 2	6.32 a	6.52 b

For ox. C concentrations, rotation was a significant main effect (P = 0.0002) in addition to sample depth (P < 0.001) but sample date was not significant (P = 0.1534). Rotation also significantly interacted with date (P =0.0118). The grain crop-initiated rotation 2 had higher ox. C values at 0.504% than both the pasture-initiated rotation (0.443%) and grain crop-initiated rotation 1 (0.448%) (SEM 0.0085, HSD 0.0451). The depth effect was due to the 0-15 cm samples having higher ox. C concentrations at 0.604% than the 15-30 cm samples at 0.329% (SEM 0.0069, HSD 0.0213). For the rotation by date interaction, the grain crop-initiated rotation 2 had significantly higher ox. C values than the two other rotation treatments for the May 2000 sample date (Figure 4.2). The pH model, including the rotation*depth*date, found this interaction not significant (data not presented).

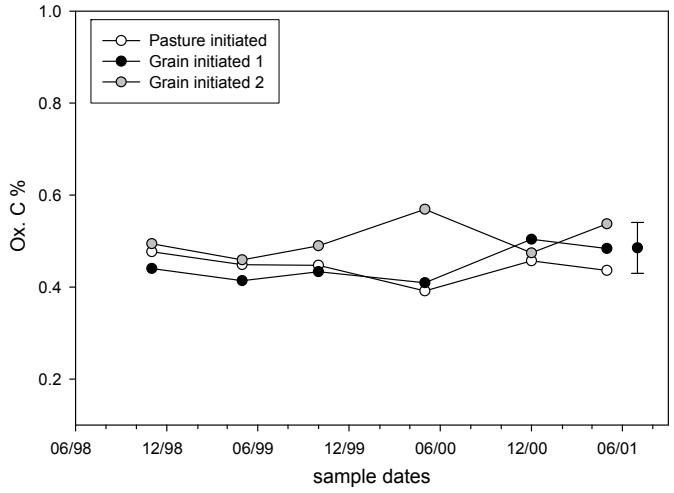

Figure 4.2. Soil oxidisable C (ox. C) % values at six sample dates from 1998 to 2001 for samples from Phases 1, 2 and 3 (SEM 0.0208, HSD error bar 0.1105)

Ley pasture species effects on pH and ox C: The effects of grazing were not reinvestigated in this subset of the prior larger set. The objective for this set containing only data from the pasture and grain-initiated rotation 1 was to investigate ley pasture species treatment effects.

For the pH model, including ley pasture species, rotation (df = 31) was a significant factor (P < 0.001), which again highlighted differences between the pasture and grain crop-initiated rotation 1 treatments in the three

rotation comparison analysis (Figure 4.1). Ley pasture species had a significant effect ($P < 0.001$) in addition to date ($P < 0.001$) but not sample depth ($P = 0.4396$). Ley pasture species also significantly interacted with date ($P = 0.011$) and with phase ($P = 0.0131$). No other interactions or main effects were significant.

For the ley pasture species*rotation interaction, the pH in the Cavalcade was lower than in the MP in the pasture-initiated rotation but not significantly. But for the grain-initiated rotation 1 the difference was significant (Figure 4.3). In addition, the Cavalcade in the grain-initiated rotation 1 had a lower pH than the Cavalcade in the pasture-initiated rotation. But for the MP treatments in each phase, differences were not significant.

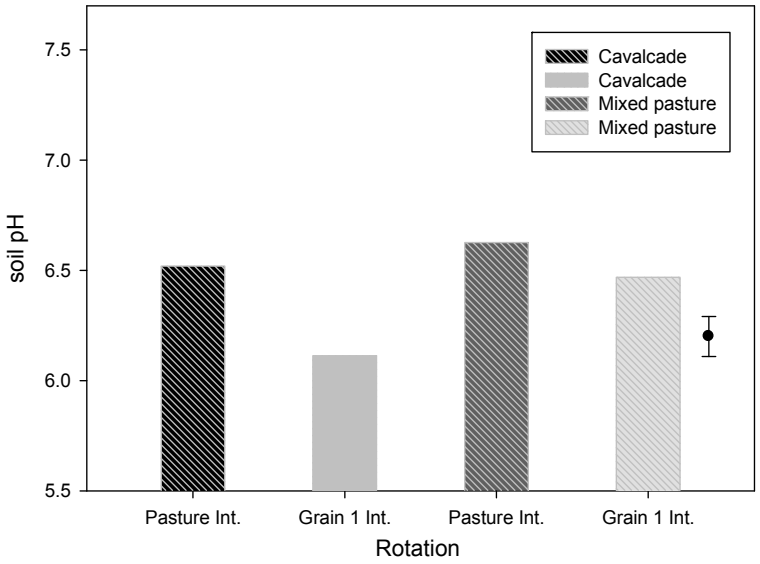

Figure 4.3. Ley pasture treatments of Cavalcade or mixed pasture for the Pasture (Pasture Int.) and grain-initiated rotation 1 (Grain Int. 1) on oxidisable C % values and SEM 0.047 and HSD error bar 0.182

For this model, rotation was not a significant factor on ox. C concentrations, ($P = 0.9844$) which reinforced the prior findings with the larger data set (Figure 4.2). Depth had a significant ($P < 0.001$) effect with 0.578 and 0.313% for the 0-15 cm and 15-30 cm sample zones, respectively (SEM 0.0082, HSD 0.0236). Ley pasture species had no significant main effect ($P = 0.1077$), but did significantly interact with date ($P = 0.0078$) and with rotation ($P = 0.034$). No other interactions or main effects were significant.

For the interaction of ley pasture species by rotation, for the grain-initiated rotation 1, MP had the lowest overall ox. C values (0.425%) with the Cavalcade ley treatment in this rotation having significantly higher values (0.470%) (Figure 4.4). In contrast, in the pasture-initiated rotation, the two ley pasture species did not differ in ox. C values.

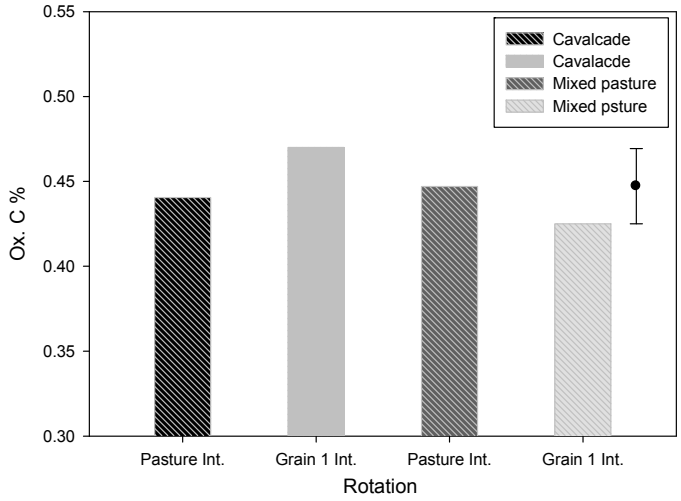

Figure 4.4. Effects of ley pasture treatments of Cavalcade or mixed pasture for the Pasture (Pasture Int.) and grain-initiated rotation 1 (Grain Int. 1) on oxidisable C (ox. C) % values, SEM 0.0116 and HSD 0.0443

4.3.4 Evidence for longer term change

Analysis for changes over time in soil pH and ox. C values were carried out with results from samples collected from common depths. The most common two sampling depths were the 0-15 cm and 15-30 cm zones. Analyses focussed on these results. For most rotations the earliest samples often had a higher pH than those of later samples (Appendix 7) but there were often breaks in sampling continuity for common depth samples between early trial and later trial period.

For the soil pH comparisons for the 0-15 cm sample zone for both the Cavalcade and mixed pasture treatments in the grain-initiated rotations, there were significant declines in soil pH over time (Table 4.13). The pasture-initiated rotation had a significant decline for the Cavalcade ley only. The slope of relationships was steeper for ley treatments in the grain-initiated rotation 1 than in the grain-initiated rotation 2 treatment. Figure 4.5 shows examples of significant negative linear relationships for the grain-initiated rotation 1 and Field 19.

For samples from the 15-30 cm zone, only the grain crop-initiated rotation 1 had significant declines for both ley pasture species treatments (Table 4.13). The other case of a significant pH decline at this depth was for one of the grain crop-initiated rotation 2 treatments. The relationship for the Cavalcade ley in the pasture-initiated rotation approached significance with a P value of 0.0502.

For the separate conventional tillage and no-tillage samples available from 1999 onwards in Field 19, there was no evidence of consistent tillage differences in pH at either the 0-15 cm or 15-30 cm samples depths (Appendix 7).

Table 4.13. Summary of R^2 and P values from linear regressions of soil pH as a dependant variable of time (cumulative numbers of days between samples) for each rotation treatment (Pasture initiated, Grain crop-initiated 1 and 2) and ley pasture species treatments. Field 19 was in continuous grain sorghum, only no-tillage samples are analysed here.

	Depth		0-15 cm		Parameters for significant regressions
Rotation	**Ley pasture species**	**n**	**R^2**	**P**	
Pasture	Mixed pasture	9	0.6139	0.0786	-
Pasture	Cavalcade	9	0.8107	0.0084	y = -0.0006(x) + 7.6435
Grain 1	Mixed pasture	8	0.8932	0.0028	y = -0.0010(x) + 7.7217
Grain 1	Cavalcade	8	0.8732	0.0046	y = -0.0009(x) + 7.2268
Grain 2	Cavalcade- mixed pasture	8	0.7830	0.0216	y = -0.0007(x) + 7.2472
Grain 2	Mixed pasture- Cavalcade	8	0.7268	0.0411	y = -0.0007(x) + 7.1876
Field 19	-	9	0.9478	0.0001	y = -0.0011(x) + 7.6500

	Depth		15-30 cm		
Rotation	**Ley pasture species trt.**	**n**	**R^2**	**P**	
Pasture	Mixed pasture	10	0.5296	0.1154	-
Pasture	Cavalcade	10	0.6315	0.0502	-
Grain 1	Mixed pasture	8	0.8223	0.0122	y = -0.0006(x) + 7.0973
Grain 1	Cavalcade	8	0.7653	0.0269	y = -0.0007(x) + 6.8703
Grain 2	Cavalcade- mixed pasture	8	0.7088	0.0490	y = -0.0004(x) + 6.9470
Grain 2	Mixed pasture- Cavalcade	8	0.5588	0.1499	-
Field 19	Ley pasture species trt.	8	0.6225	0.0993	-

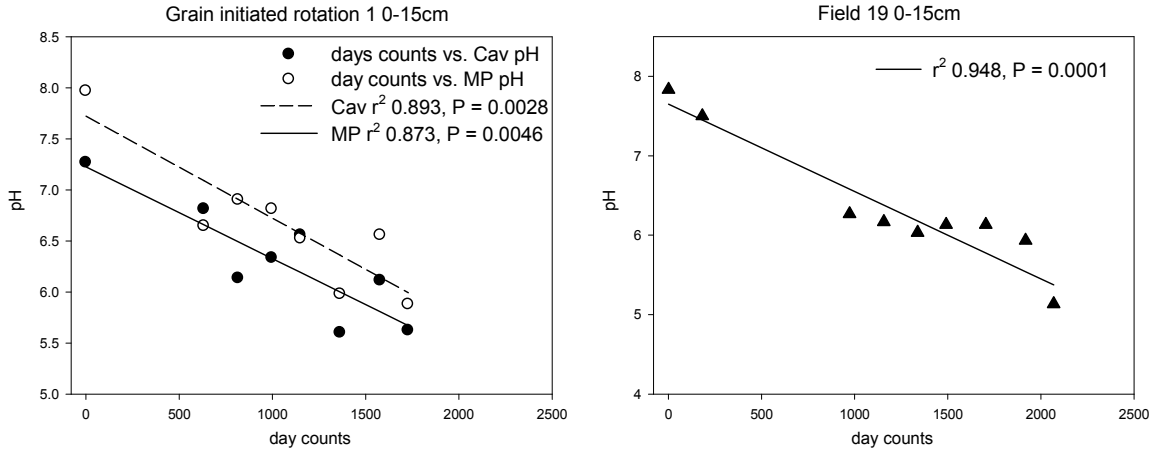

Figure 4.5. Soil pH for 0-15 cm samples showing examples of significant linear regressions for the Grain initiated rotation 1 treatment presented by ley pasture species treatments, Cavalcade (Cav.) and mixed pasture (MP) and no-tillage samples from Field 19 in continuous sorghum, multiple r^2 values and P values for significant linear regressions are presented

For the soil ox. C concentrations for the 0-15 cm sample zone, there were contrasting results between significant increases in ox. C concentrations for the Cavalcade ley treatment in the grain-initiated rotation 1 but no significant change for the mixed pasture ley treatments in any rotation treatment (Table 4.14). An example of the grain initiated rotation 1 is presented in Figure 4.6. For both ley pasture species in the grain initiated rotation 2 there were no significant declines or increases. But overall for the 0-15 cm zone most rotations had neither a significant decline nor an increase. Plots of mean values in Appendix 7 illustrate this trend.

A significant decline in ox. C concentrations for the 0-15 cm zone was observed for the no-tillage samples from Field 19 in continuous sorghum (Table 4.14 and Figure 4.6). Plots of the two tillage treatments from 1999 to 2001 showed a trend for the conventionally-tilled treatment to have lower ox. C concentrations than the no-tillage treatment plots (Appendix 7).

For samples from the 15-30 cm zone only, there were no findings of significant increases or declines in any of the ley pasture treatments in any of the rotations or the sorghum control (Table 4.14). The plots of the conventionally-tilled treatment also did not indicate any consistent difference between tillage treatments at this sample depth (Appendix 7).

Table 4.14. Summary of R^2 and P values from linear regressions of oxidisable C values as a dependant variable of time (cumulative numbers of days between samples) for each rotation treatment (Pasture initiated, Grain crop-initiated 1 and 2) and ley pasture species treatments, Field 19 was in continuous grain sorghum, only no-tillage samples are analysed here

	Depth		**0-15 cm**		**Parameters for significant regressions**
Rotation	**Ley pasture species**	**n**	**R^2**	**P**	
Pasture	Mixed pasture	9	0.2484	0.5192	
Pasture	Cavalcade	9	0.4024	0.2829	
Grain 1	Mixed pasture	8	0.0663	0.8761	
Grain 1	Cavalcade	8	0.7490	0.0325	y = 0.0001(x) + 0.5243
Grain 2	Cavalcade- Mixed pasture	8	0.2740	0.5115	
Grain 2	Mixed pasture- Cavalcade	8	0.6648	0.0721	
Field 19	Ley pasture species trt.	9	0.7213	0.0283	y = -0.0001(x) + 0.6735

	Depth		**15-30 cm**		
Rotation	**Ley pasture species**	**n**	**R^2**	**P**	
Pasture	Mixed pasture	10	0.5423	0.1053	-
Pasture	Cavalcade	10	0.2375	0.5089	-
Grain 1	Mixed pasture	8	0.4728	0.2367	-
Grain 1	Cavalcade	8	0.5476	0.1600	-
Grain 2	Cavalcade- mixed pasture	8	0.3581	0.3837	-
Grain 2	Mixed pasture- Cavalcade	8	0.0223	0.9581	-
Field 19	Ley pasture species trt.	8	0.4317	0.2855	-

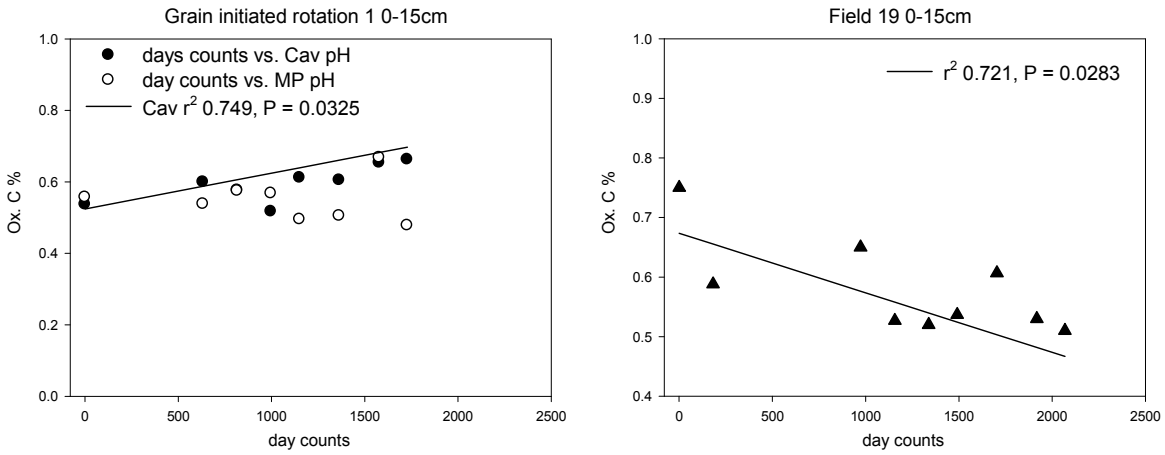

Figure 4.6. Soil oxidisable C (ox. C) % values for 0-15 cm samples showing examples of significant linear regressions for the grain initiated rotation 1 treatment for ley pasture species treatments of Cavalcade (Cav) and mixed pasture (MP) and no-tillage samples in Field 19 in continuous sorghum, multiple r^2 values and P values are presented for linear regressions

5 GENERAL DISCUSSION

This study examined soil pH and ox. C results from three trials at DDRF. The trials were useful in providing information on the effects of agricultural practices on these aspects of soil quality.

The methods used to determine soil C in the three studies limit the relevance of the data for purposes of soil C accounting and sequestration assessments (McKenzie et al. 2000). Removal of large components by sieving and the absence of bulk density information in all but one instance (Rotgut 1996) are examples of limiting methodologies. However, bulk density assessment is not typically a requirement of on-farm agricultural soil quality monitoring (Freebairn and King 2003; Schwenke et al. 2003; Ridley et al. 2007; Golchin and Asgari 2008; Kelly et al. 2009; Zagal et al. 2009). Soil quality indicators used in on-farm agricultural projects are often selected using the criteria of being simple enough so that land managers can carry out sampling. In contrast, the accurate determination of bulk density requires specialised equipment, experienced personnel and requires a large investment of time per site, especially if multiple samples per depth zone are to be collected (Dalgliesh and Foale 1998; McKenzie et al. 2000).

When comparing results between trials, it is important to note that there were differences with trial designs and sample collection methods. The Rotgut trial used a randomised complete block design, which would have provided some statistical consideration of spatial variation in soil properties. In the Systems trial, multiple samples were collected at most sample dates from each treatment as shown in Table 4.4. These multiple samples allowed average values to be used for most comparisons and the effect of single aberrant values would be diluted. However, the Systems trial was not replicated, which meant that there was no statistical consideration for spatial variation in soil properties between treatments. Finally, the Species trial had no replication and no statistical consideration for spatial variation in soil properties, and for most sample dates, results were usually available for only one sample per pasture treatment in each field, from three cores. More intensive sampling (ten bulked cores per sample) had a significant effect on pH values in the Species trial (Table 2.7). This was in spite of the absence of any strong north-south pH or ox. C gradients at the site (Appendix 2). In general, the Species results may be expected to be more variable than results from the Rotgut and the Systems trials. When interpreting results from the Species and Systems trials, it should be noted that some unaccounted spatial variation in soil properties may confound treatment effects. It is also notable that the analyses used generally only considered linear trends for soil pH and ox. C and that non-linear relationships may also be relevant to some relationships discussed.

For the Systems trial, the ability to make comparisons between rotation treatments for the same time periods was limited. It is acknowledged that the findings from the regression of sample values against time for this trial were influenced by the samples used in comparisons. For example, for the control field with continuous sorghum, samples were available from both mid and late 1995, but samples for the three rotation treatments were not available for this period. So although some comparisons between rotations, ley pasture species and grazing treatments can be made, strong conclusions should not be made when comparing results from differing time series. For the Systems trial, an appropriate view may be to regard findings as relevant to specific sub-trials (e.g. rotations) of the whole trial. This is especially the case when comparing data collected at different points in time.

This general discussion focuses on experimental findings relevant to identifying the effect of agricultural practices on soil quality and the use of soil pH and ox. C as indicators of soil quality under agricultural management.

5.1 SOIL CARBON

5.1.1 Cultivation effects

The Rotgut trial showed that no-tillage cropping practices in the Douglas Daly region environment led to significantly higher ox. C concentrations in comparison with conventional tillage (Figure 3.1). Ox. C concentrations in the surface (0-5 cm) and 15-30 cm zones (Table 3.3) were on average 0.25 and 0.175%, higher in nt compared with ct. A previous analysis of the tillage effects in this trial on ox. C contents in 1992-1993 (after eight years of nt or ct) found the nt treatment for the 0-5 cm depth had higher ox. C levels (1.05%) than the ct treatment (0.63%) (Thiagalingam et al. 1994). This is a difference of ~0.40%. The lower two sample depths (5-15 cm and 15-30 cm) were unaffected by tillage. The eight year period (1992-2000) covered by this report started seven years after the treatments were implemented in the 1984-85 season, although soil analyses for every year in this period were not available. The results from this period showed that there are benefits of nt to ox. C in the deeper 15-30 cm zone, in addition to those at the surface 0-5 cm. These findings are in contrast to a nine-year sub-tropical tillage comparison in Southern Queensland where the ox. C content of the 0-10 cm zone was higher for an nt treatment in comparison with minimum tillage and reduced tillage treatments, but there were no significant differences between 0-20 and 0-30 cm zones (Thomas et al. 2007).

It was notable in the Rotgut trial that there was no difference in ox. C contents for the 5-15 cm zone between tillage treatments. This may be due to the effects of the offset discs in the ct treatment resulting in the incorporation of crop and weed residues which increased the ox. C contents in this zone. This interpretation is supported in a tillage comparison study where soil at 15 cm sample depths under conventional mould board ploughing followed by discing had the greatest combustible C content in comparison with shallower or deeper sample depths, while a nt treatment had the highest content near the surface (Sun et al. 2011).

In contrast, a continuous nt sorghum treatment in the Systems trial on a recently cleared low clay content soil (Blain) had significant declines in ox. C values over a seven year period (Table 4.14 and Figure 4.6). A shorter period comparing ct and nt treatments showed a trend for greater deceases in ox. C concentrations under ct than nt treatments (Appendix 7), while some mixed cropping pastures in this trial had increases in ox. C concentrations (Table 4.14 and Figure 4.6).

In the Systems trial, one explanation for increases in ox. C for pasture treatments and declines in ox. C under continuous sorghum, was that the cover provided by ley pasture in two of each three-year rotation period assisted in reducing surface runoff containing crop residues and sediments on the relatively light Blain soil. During the sowing and establishment period for sorghum (late December to February), high intensity rains cause surface runoff. Although nt cropping has less runoff than conventionally cropped land, comparatively pasture has the least (Mollah 1986; Dilshad and Jonauskas 1992; Dilshad et al. 1996; Mollah and Cook 1996). The large amount of labile C present at the surface of no-tillage soils (De Bona et al. 2008) may contribute to a greater potential for losses of labile C during heavy rain and surface flooding in comparison with pasture on light soils.

These results indicate that increases in ox. C concentrations through the soil profile can occur with the continued use of nt practices in this environment on soils with a relatively high clay content (e.g. Tippera).

5.1.2 Fertiliser effects

The application of urea treatments to the Rotgut trial provided some useful observations on the relationship between N and soil C in the Douglas Daly environment. A pre-emergence application of urea at rates of 70 and 140 kg/ha was, after two months, associated with reductions in ox. C concentrations (Figure 3.3). The extent of the ox. C reduction was greater for nt due to the higher initial ox. C contents in these surface zones (Figure 3.4). This urea effect was also large, so much so that for both nt and ct plots receiving urea, there were no significant differences in ox. C concentrations, whereas significant differences were evident without urea treatments (Figure 3.4).

The effects of nitrogenous fertiliser application to plant residue breakdown, biological activity and mineralisation of organic matter may be expected to be greatest where residues have a high C: N ratio and soil nitrate levels or environmental conditions are limiting to biological activity (McLaren and Cameron 1984; Dalal and Carter 2000). During the wet season in the tropics, environmental conditions are not usually limiting to biological activity due to high soil temperatures and seasonal rainfall (Lal 1985). However, in the semi-arid environment of the Douglas Daly region, rainfall is sporadic even in the dry season (Mollah 1986; Mollah and Cook 1996). For example, in the wettest month of the year, February, on average there are only 7.5 days a month with rainfall greater than 10 mm (Anon 2011). In addition, Tippera soils have a narrow range of volumetric soil moisture contents at which water is readily available to plants due to a high proportion of kaolinite in the clay fraction (Slatyer 1954; Slatyer 1955). In early work on the Rotgut trial and in other tillage comparison trials in this region, it was shown that nt plots had higher soil moisture levels at sowing than ct plots due to a greater retention of moisture from pre-sowing rains (Van-Cuylenburg 1989; Thiagalingam et al. 1991a). The improved water retention in the nt treatment in addition to the provision of additional N through nitrogenous fertiliser application, may have provided conditions suitable for a greater period of biological activity for the mineralisation of ox. C in the nt treatment in comparison with the ct treatment. There are also reports for the microbial biomass in surface zones (0-5 cm) being higher in nt than in ct treatments (Sun et al. 2011). A larger microbial biomass could also contribute to greater mineralisation of labile C fractions in nt treatments when soil moisture conditions are suitable.

The importance of N to residue breakdown in nt treatments was also indicated in an earlier ammonium nitrate sub-trial to the Rotgut experiment. In work on maize during phase one of the experiment, there was a greater yield response to ammonium nitrate application for nt compared with ct treatments (Thiagalingam et al. 1991a). That result was attributed to the faster breakdown of cultivated incorporated residues in ct treatments, which provided a N source resulting in a reduced ammonium nitrate application response in comparison with the nt treatments where residues reside at the soil surface and breakdown rates are slower (Thiagalingam et al. 1991a). These findings indicate that the additional urea treatment in 1996 would have assisted in the breakdown of residues and mineralisation of organic matter in nt plots that may otherwise have been limited by N availability, thereby contributing to a reduced ox. C concentration in the nt treatment. Broadly, these findings indicate that both nitrate availability and soil moisture conditions are important factors affecting soil ox. C contents in this environment. Further work would be required to establish if at later time points urea applications increased crop dry matter production, increasing soil C. Although the Species and Systems trials received fertilisers, these were not applied as experimental treatments. Therefore, it is not possible to compare the Rotgut findings with these trials.

Therefore, when measuring ox. C concentrations in wet season crops, some months after urea application, it may be expected that the urea application will be associated with reduced ox. C concentrations.

5.1.3 Crop effects

Two trials (Species and Systems) had concurrent crop treatments allowing investigation of the effects of crop type on ox. C concentrations.

For the Species trial, there was no strong evidence of differences between pure grass and grass/legume (non-woody species) effects on ox. C concentrations. A review of pasture composition studies had identified that grass/legume pastures were associated with higher concentrations of soil C than pure grass pastures (Dalal and Carter 2000). However, total C values at the 15-30 cm depth were significantly higher under the tree legume leucaena (0.36 %) than the pastures in those fields (0.31%, fields 45, 48 and 534) (Table 2.10). Leucaena has also been found to contribute to higher soil C (total C method) concentrations relative to native pastures and continually-cropped land in Queensland (Radrizzani et al. 2011). Another study had found that leucaena had higher ox. C values (modified W-B method) at a depth of 30-70 cm while sabi grass had a higher content at the 0-20 cm sample zone (Noble and Jones 1997). Another study reported that increases in soil C 10 years after the establishment of leucaena occurred at depths of approximately 0.2 to

1 m but that relative to native pasture, soil C concentration declined under leucaena at depths less than 0.1 m (Dalal and Carter 2000). The larger root system of leucaena, which is deeper than that of the grass species, is probably responsible for the increased total C at the 15-30 cm depth in our study.

For the Systems trial, there were contrasting findings of the effects of mixed pasture and pure legume ley treatments. For data covering three seasons (November 1998 to May 2001) the Cavalcade ley pasture treatment had significantly higher ox. C than the mixed pasture treatment, but this was not the case between these species treatments in another rotation (Figure 4.4). But earlier results from February 1996 for the pasture initiated rotation in the second year of ley pasture found the mixed pasture to have higher ox. C concentrations than the Cavalcade pasture (Table 4.8). Results from these separate data sets highlighted that differences between the two ley species treatments were often rotation or sample date specific, and so appeared to prohibit the drawing of general conclusions about differences in effects between pure Cavalcade and Cavalcade-sabi mixed pastures on soil ox. C concentrations.

In contrast to the above findings, a plot of all available data for the ley pasture species treatments by rotation showed that for the 0-15 cm sample depth, the ox. C concentrations increased significantly in the Cavalcade ley in one rotation treatment but not in the mixed pasture ley in any of the rotations (Table 4.14). This finding differed from a Queensland study that found higher soil C contents in mixed pastures than pure legume pastures (Bruce 1965). The findings of our study could be particular to Cavalcade in the semi-arid Douglas Daly environment. Tropical mixed pastures are thought to have greater ox. C concentrations than pure legume pastures due to N fixation by legumes, benefiting grass growth and leading to greater net soil C inputs for mixed pastures (Dalal and Carter 2000). Soils used for agriculture in the NT are naturally quite low in nutrients, including the ‘Blain’ or ‘Deep Red Magnesic Kandosol’ at the Systems trial site (Williams et al. 1985; Hill et al. 2011) and rainfall is temporally variable (Mollah 1986; Mollah and Cook 1996). A possible explanation for these findings is that the N fixed by Cavalcade in a mixed pasture only benefited sabi grass during short-term favourable periods.

There was evidence of differences in associated ox. C concentrations under some plant species used in this study.

5.1.4 Seasonal effects

Both the ox. C and total C results for 2010 and 2011 Species samples and ox. C results for earlier samples showed that there can be large seasonal variations in soil C concentrations (Table 2.8 and 2.9). A seasonal effect was also evident in the other trials; for example, samples collected from the Systems trial in the wet season of February 1996 for the pasture initiated rotation had higher ox. C concentrations at the 15-30 cm depth than any samples collected in the dry season (May) or end of dry/early wet (November-December) (Table 4.9 and Appendix 7). Ox. C in the Rotgut trial for the period from 1992 to 2000 was also variable with interactions between tillage treatment and year being common (Figure 3.1). Soil moisture has been shown to have a large effect on labile C fractions under nt and ct management in the Brazilian sub-tropics. Supplementary sprinkler irrigation during dry periods led to lower labile C fractions in nt than ct treatments but this ranking was reversed in non-irrigated nt and ct treatments (De Bona et al. 2008). The wet season in tropical or semi-arid environments is identified as a period in which organic matter mineralisation and crop residue breakdown rates are high (Jenkinson and Ayanaba 1977; Lal 1985; Noble et al. 1998). The ox. C variation between seasons may therefore be partly due to the variable amount and timing of rainfall each wet season in the semi-arid Douglas Daly region environment.

However, an attempt to relate changes in ox. C concentrations to rainfall for a period of the Species trial demonstrated that the relationship was not simple. With no consistent decline in ox. C values between pre-wet season and post-wet season samples (EW-D sequences) mean levels only decreased in one of four EW-D sequences. In contrast, decreases in ox. C values occurred for three of four D-EW sequences. Differences between seasons may be due to the extent of C accumulation and mineralisation of organic

matter prior to sampling. An attempt to relate increases and decreases in ox. C values to rainfall prior to sampling for Species trial data also did not provide any clear findings. The inclusion of measurements of C inputs and measurement of factors known to contribute to C breakdown across multiple time-points may be required to better understand the seasonal variations in soil ox. C concentrations under these pastures on this soil type. Although pasture treatments were relatively stable in the Species trial, differing pasture productivity between wet seasons and interactions with grazing intensity would also be expected to affect soil C inputs.

Additional seasonal effects on ox. C concentrations in the Rotgut and Systems trials could also be partly due to changes in crop species grown annually or with crop rotation (pasture-sorghum) changes contributing to differing volumes and C:N qualities of surface trash inputs, root C inputs and C breakdown rates between crop types for effects on soil C (Lal 1985; Hulugalle et al. 1997; Hulugalle et al. 2006; Mathers et al. 2007).

Because of large seasonal effects on soil C values, sampling strategies need to ensure that annual or biannual monitoring is made when environmental conditions are relatively stable. The mid dry season or mid wet season are recommended.

5.1.5 Agricultural system effects

This report compared a continuous pasture, continuous cropping and a ley crop rotation trial. Each of the trials had different start dates and ran for different periods although results for the three trials covered a similar period. The ability to make direct comparisons between trials was limited but some observations about the longer term effects on soil C (defined in this report as an increase or decline in values evident over three or more seasons) rather than seasonal variation of these systems were made.

Some increases in ox. C concentrations were found for a Cavalcade ley pasture treatment over a six-year period (1994-2001) in the Systems trial but such an increase does not occur in the Cavalcade ley pasture treatment in two of the three rotations (Table 4.14). In contrast, ox. C results from longer term pastures in the Species trial showed little evidence of significant and consistent increases in ox. C concentrations (Table 2.13). The Species trial was important as data included seven years of continuous records (1994-2001) and also included some pastures that had been established prior to 1990 or in 1990. There was evidence of increases over four to five year periods in some fields (Fields 46 and 51), but these increases were not maintained (Figures 2.5 and 2.7). This was an exception to the norm. Soil C results from 2010 and 2011 could not be directly compared with earlier values due to the differences in soil C measuring methods. But neither did the original values or estimated modified W-B values based on a correction factor (1.27) (Meersmans et al. 2009) indicate that inclusion would have possibly provided a significant relationship. Overall, for the Species trial results showed that season to season and year to year there were fluxes in ox. C concentrations.

Results from the continuously-cropped Rotgut trial were available from 1992 to 2000. The trial had started in 1984 and although there was a significant no-tillage benefit to ox. C concentrations, values were actually variable season to season with no consistent pattern of season-on-season increase over the 1992 to 2000 period (Figure 3.1).

The ley pasture rotations in the Systems trial area were intermediate in terms of disturbance between the continuous cropping of the Rotgut trial and the continuous pastures of the Species trial. Overall, the Systems fields had higher levels of fertiliser inputs than the Species trial, especially for the sorghum crop in the mixed cropping rotation (Tables 2.1 and 4.3). The increases in ox. C concentrations observed in a Cavalcade ley pasture treatment in the Systems trial may be due to the Cavalcade ley benefiting from inputs to the preceding sorghum crops in the rotation. However, the Species results also indicated that periods of ox. C increases can occur in some fields but are not indefinite (field 51, Figure 2.5). Therefore, it is possible that a

long-term plateau of ox. C concentrations in the Cavalcade rotations would be reached around which annual fluxes in seasonal concentrations will occur.

One of the clearest findings for the effects of differing agricultural land use was the decline in ox. C concentrations in the continuous no-tillage sorghum treatment compared with a no decline or increase of ox. C in some ley rotation-mixed pasture treatments in the Systems trial. The effect of soil type in relation to these findings is discussed in Section 5.17.

Overall, the results of trials of different agricultural land use tentatively indicate that the effect of continual cropping is soil-type specific and that rotations of Cavalcade ley pastures following fertilised grain crops can provide small increases in ox. C concentrations over five to six year periods. However, it is unclear if the observed increases in the ley rotation, including Cavalcade pastures, would have continued for longer periods and if these values represent actual increases or the maintenance of pre-clearing ox. C concentrations. These areas will require further investigation.

5.1.6 Sampling depth

For all three trials, samples from different depths usually differed significantly in ox. C concentrations. Although based on limited comparisons, there was some evidence from the Rotgut trial that the vertical distribution of ox. C differed between land under agricultural management and uncleared land with native vegetation (Table 3.6 and Figure 3.7).

The implications of these findings are that appropriate depths need to be sampled. For example, in relation to the sampling of no-tillage cropped land changes in ox. C concentrations may be expected in the surface horizons before deeper horizons. Therefore, some relatively shallow sampling depths (e.g. 0-5 cm) need to be included in the overall sampling strategy.

5.1.7 Soil type effects

Two trials were on a 'Blain' soil (Species and Systems) and one on a 'Tippera' soil (Rotgut). Blain soils have a lower clay content than Tippera soils (Hill et al. 2011). Soil type is regarded as an important factor affecting soil C concentrations; for example, higher ox. C concentrations were found in clay loams than in sandy loams in southern Australia (O'Brien et al. 2003). Sandy soils with low clay contents are identified as more prone to labile C fraction losses from disturbance events such as cultivation (Dalal and Carter 2000). It was notable that the continuous no-tillage cropping of sorghum on Blain soil in the Systems trial was associated with a significant decline in ox. C concentrations in the 0-15 cm depth over six cropping seasons after native vegetation clearance (Figure 4.6). Although a similar comparison following clearing was not available for the Rotgut trial, comparisons indicated substantial differences in ox. C concentrations. For example, average ox. C values were ~0.5% in 2001 for the 0-15 cm depth in the Systems continuous sorghum while the Rotgut trial had average values of 1.1 and 0.7% for the 0-5 cm and 5-15 cm depths in nt treatments for a nine year period starting six years after the trial had started (Table 3.3 and Figure 4.6).

The differences in ox. C values observed between the two different soil types in these trials support the development of soil type specific thresholds for soil C values when assessing the effects of agricultural practices.

5.1.8 Soil C measurement methods

This study largely used historic soil C results from a modified W-B method. This method seeks to provide soil C results close to that achieved from total C combustion methods. However, it is particular labile fractions that are most affected by some agricultural practices, such as cultivation (Dalal and Carter 2000). Some Australian studies have also found for semiarid pastures that mild oxidising conditions can separate pasture management sensitive C fractions but the W-B method did not (Chan et al. 2001), that fractions of total C associated with aggregate resistance to breakdown by heavy rainfall, were lower in cultivated fields (Bell et al. 1999) and that more mild oxidising methods than the W-B method were required to identify land use

change effects (Mendham et al. 2002). Although the ox. C method used for the analysis of historic samples was useful, some quantification of the proportion of total C recovered by this particular modified W-B method on these soil types is also required. If this particular modified W-B method is recovering a high proportion (for example, over 80%) of total C, then methods that measure particular labile fractions of soil C may be more useful as monitoring tools. But, if the methods to measure particular labile fractions are adopted, measurements of total C should also be made in order to estimate changes in total C relative to particular fractions.

For agricultural soil quality monitoring to be effective, appropriate soil C measurement methods that are sensitive to agricultural practices need to be used. There is a need to identify a sensitive soil C measurement method for agricultural soil quality monitoring in the NT.

5.1.9 Land clearance effects

The trials provided some comparisons between cleared land under agricultural management and uncleared land. A comparison of Rotgut treatments with an uncleared area in 1996 indicated some differences, including ox. C concentrations (Figure 3.5). However, there are a number of potential contributing factors that should be considered when interpreting these results.

It has been recommended that, when sampling soil under native vegetation, suitable replication is employed to counter the effects of high soil C variability associated with the effects of heterogeneous vegetation (Allen et al. 2010). The importance of vegetation effects on soil C concentrations in NT soils was reinforced in a recent study (Hancock et al. 2010). On the basis of these studies, it is probable that the collection of more than three samples or greater subsampling per bulked sample may have provided a more representative result. In addition, most of the area surrounding the Tippera experimental site had also been used for rough grazing at different times and some of the research areas were protected from fire for some periods (Lucas 1984). Both grazing and fire could have affected ox. C comparisons between the bush and Rotgut soils. The prior and subsequent sampling of the Rotgut trial in other years provided some ability to verify the representativeness of the 1996 results. But it was not possible to do this for the results from the bush samples. Finally, the results presented in this study are single time-point observations and may not represent the treatment rankings if samples were taken at other times of the year or in other years. Despite these limitations, the 1996 comparison provided useful findings on ox. C distribution by depth and concentration in these differing land uses.

It is also important to note that there was general support for the bulk density values used for calculating the area and volumetric ox. C concentrations in the uncleared bush for the nt and ct arable management practice comparisons. The accuracy of bulk density values have a large effect on area and volumetric C calculations (McKenzie et al. 2000). A study of uncleared bush in Howard Springs in the NT found bulk densities in a range from 1.42 g cm^3 at 5 cm depth to 1.7 g cm^3 at 1 m (Chen et al. 2003). These values were similar in scale to those observed at similar depths in the bush site in our study (Figure 3.6 and Appendix 5). A comparison of uncleared land with grazed pastures in the semi-arid tropic of Queensland found in general that pastures that had been cleared for approximately 30 years had higher bulk densities than the uncleared sites (Sangha et al. 2005). In our study the uncleared bush had significantly less dense soil than the land under tillage treatments in the 0-5 cm and 5-15 cm profiles. This trend for increasing bulk density following clearing is consistent with the explanation that clearing and cropping can act to decrease soil pore spaces in soil relatively near the surface, even though there was evidence in our study that cleared land may have less dense soil at greater depths. Our findings, however, differed from those of another Douglas Daly region-based study on a Tippera soil in the mid-1980s where the bulk density in the top 0-5 cm surface zone of cultivated land under agricultural management after the harvest of a wet season crop (1.22 g/cm^3) was lower than that of the uncleared land (1.44 g/cm^3) (Lynch unpublished). However, Van-Cuylenburg (1989) commented on the above findings and reported that the 1.44 g/cm^3 value was comprised of separate samples from both furrows and ridges of the cultivated land and when the furrow bulk densities

were compared with the uncleared land, the cultivated land had significantly higher bulk densities than the uncleared land. Thus, these additional results also support our finding that clearing and cultivation increases the bulk density of surface zones.

The bush and arable comparison in the Rotgut trial showed that greater ox. C concentrations may be located at depth under bush than in land under agricultural management. In particular, at the 15-30 cm sample zone, there were greater concentrations for the bush (0.907%) than all Rotgut treatments except the nt nil N treatment (0.567%) Concentrations at the 30-60 cm zone were also higher for the bush but this difference was not significant. A study of a Tippera soil in the Douglas Daly region compared the top 1 cm surface zone of uncleared land and ploughed land under agricultural management for three seasons and found large differences in the ox. C (non-modified W-B method) concentrations between the agricultural area (0.95%) and the uncleared area (2.16%) (Lynch unpublished). The scale of differences between treatments (range 0.840-1.447%) was not as large in our study. This may be due to the larger sample volume of the 5-cm depth samples, which diluted the effects concentrated at shallower surface depths. This report showed that ct practices as found by Lynch (unpublished) in this environment and soil type were associated with reduced ox. C concentration in comparison with uncleared bush. But this report also found that the type of tillage and N fertiliser practices were also important factors affecting ox. C concentrations.

Prior studies identified poor capacity to improve soil C in soils under agricultural management in the tropics due to wet season environmental conditions favouring high organic matter mineralisation and high crop residue breakdown rates (Jenkinson and Ayanaba 1977; Lal 1985; Dalal and Carter 2000). However, results in our study showed that soil under some agricultural practices may be associated with similar ox. C concentration to those found in soil under uncleared bush but that the distribution by depth differs between land use. In contrast to results from the 15-30 cm and 30-60 cm sample zones, the nt nil N practice had higher ox. C concentrations in the top 0-5 cm and 5-15 cm sample zones than did the bush area (Figures 3.5 and 3.7). Other tillage comparison studies have shown that nt practices lead to an accumulation of C and nutrients in sample zones close to the soil surface (Thomas et al. 2007). Due to the greater ox. C concentrations at the surface and relatively small but important contributions at deeper depths in comparison with the other tillage and N treatments, the total kg ox. C/m^2 in the total 1.2 m sample zone of the nt nil N treatment at 8.24 kg ox. C/m^2 was very similar to that of the bush area (8.32 kg ox. C/m^2). In comparison, other Rotgut treatments had lower total kg ox. C/m^2 values by 1.6 to 2.1 kg.

However, it was notable that the ox. C values for the bush area at 8.3 kg C m^2 in the top 1.2 m were lower in comparison with another comparable area. In a study of four sites of NT coastal open forest (*Eucalyptus tetrodonta* and *E. miniata* dominant) savannah the soil ox. C (Heanes modified W-B method) content in the top 1 m zone was measured at 15.1 kg C m^2. This was a substantial proportion (about 74%) of the C content in the ecosystem (Chen et al. 2003). The lower value for the bush at DDRF may be due to vegetation type, fire history, soil fertility and prior grazing effects.

A model of soil C values under cropping following clearing in the NT identified that soil C values may increase slowly over time with the retention of stubble (Law and Garnett 2009). Our findings indicated that fertiliser and tillage practices will be additional important factors affecting potential maintenance or increases in soil C values.

Comparisons of soil C for buffel fields in the Species trial with an uncleared bush area showed no evidence of significant differences for the depths sampled (Tables 2.13 and 2.14). Other studies in Australia have found the vertical soil C distribution between native or exotic trees and grasslands to differ (Dalal and Carter 2000; Maraseni et al. 2008).

Where comparisons of agricultural land and uncleared land are being planned, it is important to follow established guidelines (McKenzie et al. 2000; Allen et al. 2010). Results from our study also showed that the effects of nitrogenous fertiliser practices on soil C values also need to be considered.

5.1.10 Soil C contributions to acidification

In Australian agricultural systems there can be a negative effect of increasing soil C concentrations contributing to acidification (Fenton and Helyar 2007; Thomas et al. 2007). For the Systems trial, there were examples of an improvement in ox. C concentration under a legume ley in conjunction with significant acidification (grain initiated rotation 1, Cavalcade ley), and to acidification occurring in four ley rotation-pasture species treatments with no significant changes in ox. C concentrations (Tables 4.13 and 4.14). Noble et al. (1998) suggested that the high rainfall of tropical areas contributing to rapid organic matter breakdown may limit the effect of organic matter on acidification. This could explain why there was no consistent association between increasing soil C concentrations and acidification in the Systems trial. In addition, the Systems trial ran for seven seasons, which was a relatively short period from which to assess potential long term effects.

Our study found no clear link between increased soil C and acidification. However, this area may require further investigation to confirm our findings.

5.2 SOIL PH

A study recently reported the pH of NT soils was in the range of 5.5 to 7.4 (de Caritat et al. 2011). Most NT soils in that study had a slight acidic to neutral pH (6-7) but some soils were acidic (4-5.5). The soils at the three trials in our study fitted approximately into the slight acidic to neutral pH category. However, in some cases, soils that were more alkaline or acidic were recorded.

5.2.1 Fertiliser effects

For the Rotgut and Systems trials there were significant declines in soil pH H_2O over time and both trials received nitrogenous fertilisers mostly as urea but also some applications of diammonium phosphate (DAP) blended with sulphate of ammonia (SOA) in later seasons. Nitrogenous fertilisers are identified as contributing to acidification in Australia (Fenton and Helyar 2007). DAP and SOA are stronger soil acidifying agents than urea (Fenton and Helyar 2007). These fertilisers were usually applied as part of standard crop husbandry practices and therefore calculating their impact is difficult. However, in the Rotgut trial in 1996 mixed split plot urea treatments which received 70 and 140 kg/ha urea, had a lower pH than the untreated control. The extent of this effect in a single season was quite large at 0.36 units (Table 3.9).

The nitrification of ammonium from N fertilisers leads to the production of nitrate (NO_3^-) and H^+ ions. Nitrate can be freely taken up by the roots and uptake increases pH by the release of alkaline compounds (hydroxyl or bicarbonate ions). If nitrate is not taken up by the crop and leached along with basic cations, it contributes to increased acidity due to the greater balance of H^+ ions (Fenton and Helyar 2007). The leaching of nitrates has been identified as contributing to the acidification of surface soils in other tillage and rotation trials in Australia (Dolling *et al.* 1994; Xu et al. 2002; Thomas et al. 2007). The contribution of N fertilisers to acidification can be substantial. For example, a study on a sandy soil in Western Australia attributed 98% of total acidification in a continuous wheat treatment to the effects of nitrate leaching from N fertilisers (Dolling et al. 1994). However, it is the amount and timing of nitrogenous fertiliser applications that are critical to reducing nitrate losses as nitrate taken up by plants does not cause acidification (Fenton and Helyar 2007). The pH results for the Rotgut urea treatment in 1996 indicated that a proportion of the nitrate originating from the conversion of urea was not being used by the crop. This may have been due to application of urea at planting rather than post-emergence, because at planting, normally during the early wet season, periods of high rainfall occur, which contribute to the leaching of nitrogenous fertilisers and nitrates from mineralised organic-N (Mollah 1986; Jones et al. 1991; Mollah and Cook 1996; Dourado-Neto et al. 2010).

The role of appropriate nitrogenous fertiliser practices in maximising plant uptake and minimising leaching are important. Poor N fertiliser recovery by crops was identified as a major factor contributing to the leaching of nitrates (Dalal 1992). The bulk of urea in the Rotgut and Systems experiments was banded at sowing with some secondary topdressing a month or two after sowing. The semi-arid environment of the Douglas Day region has both wet and dry periods during the wet season, with often short duration but intense rains (Mollah 1986; Mollah and Cook 1996). In this environment, with sandy soils, the potential nitrate leaching from fertilisers during intense rain events is high, especially when the crop is newly establishing without an effective root system. To minimise the potential for nitrate leaching, fertiliser applications would need to be progressively applied. However, the economics of repeated applications and practicality of such operations during the wet season may not be feasible.

Crops associated with high soil acidification rates, such as bananas in Queensland, had annual N fertiliser applications ranging from 320 to 620 NH_4-N kg/ha (Moody and Aitken 1997). In comparison, the rates and frequency of nitrogenous fertilisers in the Rotgut and Systems trials were comparatively moderate (Tables 3.1 and 4.3), and were comparable to rates used in Queensland to produce maize, which had one of the lowest acidification rates in the study of Moody and Aitken (1997). This information suggests that other factors in addition to the application of nitrogenous fertilisers also contributed to the observed declines in soil pH.

The pH of soil is not a static attribute. In work examining acidification following the application of differing forms of nitrogenous fertilisers, depending on the application rate, a pH 'rebound' effect was identified whereby some months after the acidification event, pH values returned to pre-treatment values (Peryea and Burrows 1999). It would be important to identify the current pH of the acidified areas of the Rotgut and Systems trials. In particular, this information would help to understand if there is some natural correction to historically agriculturally acidified areas, the extent of any correction, or if effects were permanent. This information would be useful to determine the longer term impacts of agricultural acidification in this environment.

5.2.2 Crop effects

A number of legumes species are recognised as contributing to soil acidification. As legumes improve the N status of soils, they also increase the potential for the loss of nitrate through the soil profile (leaching) and so are associated with greater rates of acidification than non-legumes. In addition, N fixation releases hydrogen ions, exacerbating acidification (Moody and Aitken 1997; Noble et al.1998; Fenton and Helyar 2007). For example, soils under pastures of the legume *Stylosanthes* in the NT and Queensland showed significant acidification in comparison with uncleared sites (Noble et al. 1997).

The Rotgut trial's rotation was based on alternating legume (soybean, mungbean and Cavalcade) and non-legume tropical grain crops (maize or sorghum). We could find no studies that had investigated the effect of the frequency of legume to non-legume crops on soil pH in the Australian tropics, although a study found that legume crops in an arable rotation contributed to soil acidification in the Brazilian tropics (Vieira et al. 2008). However, it was unclear if the frequency of legume cropping (approx. 1:1) in the Rotgut rotation was critical to the observed acidification. Separate experiments with a range of legume cropping intensities would be required to investigate this further.

Some specific pure legume pastures have been identified as having acidification problems due to the long term effects of NH_4^+ fixed by legumes being nitrified and the leaching of nitrates and where legumes also lead to increased soil C concentrations (Noble et al. 1997; Fenton and Helyar 2007). The Species trial gave some opportunity to compare the pH of relatively long-term legume-grass and grass only pastures. We found no evidence of a lower pH or higher soil C in legume-grass samples than grass only pastures, although only a small number of comparisons could be made.

The tree legume leucaena had been shown to be associated with soil acidification in Queensland (Noble and Jones 1997; Noble et al. 1998). However, our results for leucaena compared with pastures samples in these fields found no evidence for differences in pH values for both the 0-15 cm and 15-30 cm sample zones (Table 2.10). A contributing reason for this difference is that the leucaena system studied by Noble et al (1997; 1998) was a high input system for intensive N-fertilised irrigated dairy grazing. In contrast, the management in the Species trial was a comparatively low input system (Table 2.1).

The Systems trial provided comparisons of short-term legume-grass (sabi grass and Cavalcade) and legume only pastures (Cavalcade) for effects on soil pH. Some initial findings in 1996 from one rotation treatment supported a pure legume pH effect (Table 4.7). However, results for this same rotation treatment collected in the following season after the sorghum crop showed that the lower pH associated with Cavalcade had not persisted. For this sample period the mixed pasture ley treatment had a significant reduction in pH to a level that did not differ significantly from the Cavalcade ley treatment (Table 4-9). Later results comparing two rotations also showed that there was no consistent effect of Cavalcade on soil pH (Figure 4.3). Overall, these findings did not support the legume only ley pasture treatment of Cavalcade having a consistently negative effect on soil pH.

An understanding of the effects of individual pasture and arable crop species with the exception of work on Stylosanthes on soil pH in the NT is relatively limited. Our study found no strong association with particular legume species and acidification. However, these findings would need to be independently confirmed.

5.2.3 Seasonal effects

One of the consistent observations of soil pH in this report was that there were often large variations in values between seasons, which often made the discussion of 'mean values' difficult. For example, there were significant increases or decreases in pH H_2O values between consecutive samples taken in different seasons in the Species and Systems trials (Figures 2.1, 4-1, Table 2.8) and pH H_2O and pH $CaCl_2$ results in the Species trial during two seasons (Figure 2.2, Table 2.9).

Large seasonal changes in soil pH H_2O values of up to 1.8 units have been observed in Australia (Siman et al. 1974). Temporal changes in soil pH (pH $CaCl_2$ method) were investigated in southern Australia (Conyers et al. 1997). In that study, no clear seasonal cycle was identified; rather, variation in soil pH was affected by periods of when seasonal conditions were more extreme than the average. For example, two sites had acidification trends (decreases of 0.3 to 0.35 units) following the start of late summer rains in the first year; in the second year, acidification trends occurred after a long dry summer; an alkalinisation trend (increases of 0.3 to 0.4 units) then occurred in association with soil moisture exceeding field capacity in the autumn. That study also identified that the surface 0-2 cm had much more temporally variable pH than the 2-10 cm and 10-20 cm sample zones. In a study of sub-horizons in the top 15 cm of soil the dominant pH-influencing processes were identified as net N mineralisation and subsequent nitrification, and the return of alkaline plant residues (Paul et al. 2001).

Large alkalisation trends were observed in two rotation treatments in the Systems trial from the early dry to a late dry season in the 0-15 cm sample zone (May 2000 to December 2000) and in the Species trial over the 2010-11 wet season (Figures 2.1 and 2.2). In contrast, samples taken from an area of uncleared bush close to the Species trial had no change in pH in the same sample zone over the 2010-11 wet season (Tables 2.13 and 2.14). The differences between pasture and bush could be associated with differing plant residues return or volume rates contributing to alkalisation events.

Without an improved understanding of both the range of pH values across seasons and factors affecting the variation in values, it will be difficult to interpret soil pH results for soil quality monitoring programs in this environment.

5.2.4 Agricultural system effects

The three trials in this study covered a range of agricultural land uses from continuous pasture, mixed cropping ley rotations and continuous cropping. The ability to make direct comparisons among trials is limited but some tentative observations about the longer term effects (defined in this report as an increase or decline in values evident over three or more seasons) rather than seasonal variation of these systems can be made. The findings regarding acidification over time for each trial and any support from independent sampling is discussed below for each trial separately.

Species trial: The comparison of pasture species over time found there was no evidence for linear acidification for the complete data set for each field (Table 2.11). However, for particular periods and for some fields, there was some evidence of acidification. The exclusion of the 2010 and 2011 data resulted in a significant soil acidification relationship in four of the example fields, but values from one season (December 2001) were critical to the significance of these relationships for three of the four fields (Table 2.11). Of all sampling dates, the December 2001 samples had the lowest pH values (Appendix 2). McCown (1996) had expressed concern over the ability to manage factors associated with the risk of acidification in legume pastures in a mixed cropping rotations in the semi-arid tropics. In particular, he identified the problem of low pasture interception of mineralised nitrate at the start of the wet season when pastures were inactive but short-term high rainfall events cause leaching. Rainfall records showed that there was 67 mm and 48 mm of rain in October and November 2001, respectively with 57 mm of rain falling in two days in mid-October (Anon 2011). The early rainfall in October could have led to leaching of nitrate below the pasture root zone before the plants were actively growing. However, pre-wet rainfall did not correlate with average seasonal pH declines for data from six fields from 1996 to 2002 (Section 2.31). Regardless of the cause, the lower than usual pH value for December 2001 samples show that, in this environment, great weight should not be placed on values from a single time-point. Instead, weight should be placed on trends based on samples from multiple time-points only.

Field 43 had a significantly lower pH than other fields in December 1998 (Table 2-5). This field had silk sorghum and Maldonado for two years but was cultivated, fertilised and re-sown with silk sorghum and blue pea in December 1998. From all available pH data (1984-2002) field 43 had a more narrow range of pH values than other fields (Appendix 2). Field 43 also had the most species changes of all fields with seven pasture changes since it was originally sown with sabi grass before 1990. Three other fields had between three and five pasture changes (fields 48, 50 and 51). Due to the large number of management changes and the relatively recent sowing of Signal grass in 2007, field 43 was excluded from sampling in 2010 and 2011. However, these tentative findings indicate that future studies could consider comparing the soil pH of fields with frequent pasture changes with that of long-term undisturbed pastures.

Rotgut trial: This trial showed that arable cropping (independent of tillage) can be associated with soil acidification on Deep Red Mesotrophic Kandosols in the NT. For the period of our study (1991-2000), declines in pH were substantial (0.9 units, from 6.1 to 5.2) in the 0-5 cm and 5-15 cm zones. For the 15-30 cm zone, the decline was slightly less at 0.6 units (from 6.1 to 5.5). Acidification rates over this period averaged -0.10/year and -0.07/year for the two upper zones and the 15-30 cm zone, respectively. The extent of decline in soil pH was greater than that measured at two NT Stylosanthes pastures in comparison with uncleared sites (Noble et al. 1997).

A decline in pH from arable cropping had been reported for an earlier phase of this trial (Thiagalingam et al. 1994). In that report, soil pH results from the 1991-92 season for the 0-5 cm, 5-15 cm and 15-30 cm depths with an average pH of ~6.1 were observed to have declined from an initial pH of 6.8. No reference for the source of the initial pH value was provided in Thiagalingam et al. (1994), but earlier reports of Thiagalingam et al. (1987; 1988) referred to the soil profile at the Rotgut site being described by Lucas (1984). Lucas (1984) reported that the bay in which the trial was located (bay DPP6) was a ‘Tippera clay loam’ and that ‘Tippera clay loams’ at the site had a pH of 7.0 for the 0-10 cm and 10-20 cm profiles and a pH of 6.8 for

three other profiles (20-30 cm, 30-60 cm and 60-150 cm) (Appendix 4). The initial pH value of 6.8 cited in Thiagalingam et al. (1994) appears to have been sourced from the study of Lucas (1984) but this was not confirmed. The pH values cited by Lucas (1984) are probably average values calculated from separate samples across the Tippera Experimental Site. Lucas (1984) also stated that they sampled the site in 1982 after clearing in 1981 but also incorporated results for samples collected prior to clearing in 1979 for the soil descriptions.

The pH results (acid base indicator method) from three soil description pits made in August 1979 from sites quite close to the Rotgut trial (NRETAS 2011) (Appendix 4), on the same soil type ('Tippera clay loam' areas) as the Rotgut trial as indicated from the site maps of Lucas (1984) were selected for comparisons. The pH in the top 20 cm of these soils ranged from 6 to 6.5. Two pits had alkaline trends with depth to a maximum pH of 7. One pit had an acid trend with depth to a maximum of pH 6.0. Another pit (Olloo 31) sampled in an uncleared area of adjacent bush in October 1981 had a pH of 6 at all depths (NRETAS 2011). In general, the pH at 0-20 cm in these pits was lower than the initial value of 6.8 cited by Thiagalingam et al. (1994) and lower than the summary values cited by Lucas (1984) for this soil type (Appendix 4). Different measurement methods were used for pH in the soil description pits (acid base indicator) to the analyses of samples from the Rotgut trial (water method, pH H_2O). But the differing methods may not account for the differing values, as these two methods are reported to provide similar pH values (Raupach and Tucker 1959; de Caritat et al. 2011). However, Lucas (1984) also reported that four transects each of 10 samples at both the 0-15 cm and 15-30 cm zones were collected across Block B which contained DPP Bays 4, 5 and 6. Results from these samples were not available but as soil pH is known to be spatially variable (Conyers et al. 1997), it is possible that pH values from these transects were also used to calculate the summary pH values for the 'Tippera clay loam' reported by Lucas (1984).

The pH H_2O values from unpublished results of samples collected in July 1986 from neighbouring bays in the same continuous area of the 'Tippera clay loam' were also useful for providing information of pH values for this area under agricultural and uncleared management at that time (Appendix 4). For the three cleared and cropped 'Tippera clay loam' SMP bays (SMP 3, 4 and 5), pH values ranged from 6.0 to 6.7, 6.2 to 6.7 and 6.3 to 6.6 for the 0-10 cm, 10-15 cm and 15-20 cm zones, respectively. In comparison, the uncleared SMP bay had higher pH values of 7.3, 6.9 and 7.1 for the 0-10 cm, 10-15 cm and 15-20 cm zones, respectively. As these values were for samples of 10 separate bulked subsamples per bay, and as the pH method (pH H_2O) and analysis were carried out at the same Berrimah laboratory as the Rotgut soil sample analyses, they may be more comparable with the replicated sampling for Rotgut plots than the results from NRETAS' soil description pits dug at single sites with pH determined by an acid base indicator method. These unpublished results provided some, but not conclusive support, that pH values in adjacent bays of 'Tippera clay loam' soil under cropping management were higher in 1986 than in 1992. However, results for the 0-10 cm zone had a wide range of values (0.7 units) with the lowest value at 6.0 being lower than the 1992 value of 6.1 cited by Thiagalingam et al. (1994).

In summary, for the Rotgut trial, the pH values for the uncleared area in 1986 were similar to summary values reported for this soil type by Lucas (1984) from samples collected prior to clearing in 1979 or one year after clearing in 1982; they were higher than the 6-6.5 values for the 0-20 cm zone for three pits sampled in 1979 close to the trial area; they were higher than in the 1986 cropped areas; for the 10-15 cm zone (6.9) they were similar to the initial value of 6.8 for the Rotgut area reported by Thiagalingam et al. (1994); and they were higher than the pH of ~6.1 observed in 1992 samples in the Rotgut trial. Together, these results in general indicated that pH had declined over time in the Rotgut trial.

Systems trial: For this trial, the final samples from May 2001 were from the seventh season for the first two rotation treatments and from the sixth season for the third rotation. In terms of identifying long-term effects, this was a relatively short period (Rasmussen et al. 1998). Although the duration of this study was relatively short, there was evidence of acidification in all three rotation treatments and in the continuous sorghum

control in 0-15 cm sample zone (Table 4.13 and Figure 4.5). There were also significant acidification trends in the 15-30 cm sample zone in two of the rotation treatments. Although the trial ran for six or seven seasons depending on the particular rotation treatment, data from the same depths covering this complete period was not available. The period of available data (depending on the sample depth) typically covered only four or five seasons, with the exception of samples from the continuous sorghum control. There were some breaks in sampling continuity for samples of a common depth. However, plots of pH results from similar depths provided some support that trends were similar during periods when there was no data for the same depth. One notable exception was the 1997 0-10 cm and 10-30 cm values for the pasture initiated rotation treatment, which did not support an acidification trend (Appendix 7).

The slopes of pH vs. time for the 0-15 cm zone ranged from -0.22 to -0.36 units/year and the slope for the 15-30 cm zone ranged from -0.15 to -0.26 pH units/year. These rates of acidification (especially those for the 0-15 cm zone) were higher than those reported in a number of other arable crop or mixed cropping trials in Australia, although most were carried out over a longer period than this Systems trial (Ridley et al. 1990a; Dolling et al. 1994; Fettell and Gill 1995; Helyar et al. 1997; Moody and Aitken 1997; Slattery et al. 1998; Xu et al. 2002). Due to the relatively short period of this study, it was unknown if these rates would have continued or a plateau would have been reached that would have reduced average rates.

The pH decline vs. time for the 0-15 cm depth in the continuous sorghum treatment had a slightly steeper slope than the ley mixed pasture treatment in the grain initiated rotation 1 treatment, although the continuous sorghum had data from two dates in 1995 not available for other treatments. The continuous sorghum control had, on average, larger annual additions of nitrogenous fertilisers than the ley pasture rotations, which may have contributed to the more substantial pH decline (Fenton and Helyar 2007; Schroder et al. 2011). Management practices therefore, probably have a greater effect on acidification than continual cropping with sorghum (Guzman et al. 2006).

There was no significant effect of grazing intensity treatments or interactions on soil pH in the Systems trial for data across the three rotations (Table 4.11). For one small data set (Pasture initiated rotation, February 1996 to May 1997), the medium density grazing had a higher pH than the low grazing treatment. It was also notable that these 1996-97 differences were not maintained at later sample dates and that the 1996-97 values did not support a simple grazing density relationship for high or low grazing being associated with increasing or decreasing soil pH. We therefore did not consider the 1996-97 finding of particular importance. In terms of possible effects on soil pH, the grazing treatment with the highest amount of product removal over the long term could be expected to contribute to acidification (Moody and Aitken 1997). If this effect is relevant to the trial, the trial and sample series may have not covered enough time for this effect to be apparent.

General comments on agricultural system effects: It was notable that there was no significant evidence for acidification in the continuous pastures of the Species trial for the complete data set. However, a recent Douglas Daly-based study identified an association with lower pH in soil under old pastures (cleared 25-30 years ago, 6.03) to young pastures (cleared 5-7 years ago, 6.46) (Grover et al. 2012). In some non-NT studies, perennial pastures are identified as at less of a risk of acidification than annual pastures (Ridley et al. 1990a; White et al. 2000). Our trials did not include annual pastures but some acidification did occur in both the mixed cropping ley rotations with two year pastures and in the continuous cropping trial. To evaluate the generality of these findings, further work will be required. But it is likely that site-specific and management factors are important and therefore it is not expected that all fields in the region used for mixed cropping or continuous cropping would have similar acidification problems.

In terms of selecting appropriate agricultural land use options for a region, concern had previously been raised of the potential for acidification in mixed cropping legume-based ley rotations. McCown (1996), in a discussion paper on appropriate cropping systems for the northern tropics of Australia, noted a number of

factors leading to acidification in mixed cropping with legume leys. These were rapid rates of mineralisation, freely draining soils, periods of heavy rainfall, pulses of mineralisation occurring at the end of the dry season prior to, or at, wet season crop establishment contributing to nitrate drainage through the profile, problems with acidification under legume pastures, most soils in the region having a low buffering capacity and the high cost of lime in the region.

The results from our trials showed that McCown's (1996) comments were largely accurate and a number of the factors identified also appear relevant to mixed pasture ley rotations and continuous cropping as acidification was observed under these treatments in the Systems and Rotgut trials. The length of the ley pasture period in the Systems ley cropping trial may also have been a factor affecting acidification, as a rotation experiment in Western Australia on sandy soil found that a pasture-pasture-wheat rotation added approximately twice as much acidity as a pasture-wheat rotation (Dolling et al. 1994). Similarly, a high nitrate leaching potential was identified following two years of pasture in another ley pasture rotation experiment, although the first crop following a one-year pasture-crop rotation also had high potential nitrate leaching (Helyar et al. 1997). Seasonal conditions affecting residue breakdown in the dry season and early wet may also have a large effect in the Douglas Daly environment. For example, 53% of the N in first year Cavalcade ley pasture residues was identified as being mineralised between May and November in trials at DDRF, with this nitrate considered to have been potentially leached by early wet season rains (Thiagalingam et al. 1995). For the second year ley, this figure for N mineralisation was lower at approximately 20%.

Another component that may have affected acidification in the Systems trial was the grazing of sorghum stubble. A study examining wheat-grain sorghum rotations under no-tillage showed that the wheat and sorghum crop residues were a major factor limiting acidification. The alkaline residues neutralised over 30% of the acid generated by nitrate leaching below 30 cm (Tarkalson et al. 2006). The grazing of sorghum residues in the Systems trial may have contributed to the more rapid decline in pH observed in some rotations than observed in the Rotgut trial where residues were not grazed.

A number of additional factors are known to contribute to acidification, such as the extent of crop or livestock removal, which can contribute to acidification through the removal of alkaline products from the system (Moody and Aitken 1997; Fenton and Helyar 2007). There are also natural soil-weathering processes that contribute to ongoing incremental shifts in soil pH. These factors may be also important in this environment. However, data for factors such as the extent of alkaline product removal for each of the trials, was not available for interpretation.

The results from the three trials at DDRF may be useful for identifying the potential effects of acidification among differing agricultural systems in this environment, although it will be important to investigate contemporary arable and mixed cropping systems using current best practice methods to establish their relevance. The importance of the effect of alkaline product removal from each system remains to be investigated. In some cases, DPIF holds historical soil samples that have not been analysed. Other work has shown that analyses of historical samples can provide useful findings of the effects of agricultural practices on soil quality (Noble et al. 1997). The analyses of existing samples should be considered to address some of these information gaps.

5.2.5 pH management

The results of the Rotgut and Systems trials highlighted that pH management is required in this environment. None of the trials had lime applied. A number of agricultural areas of Australia do not use lime or use little lime due to the prohibitive cost of transporting lime to these particular regions (Conyers et al. 1996; McCown 1996). However, results from the Rotgut and Systems trials showed some form of pH management will be required if similar cropping programs are to be carried out, especially as is expected that continued production on acidified sandy soils will lead to reductions in yields (Ellmer et al. 2000; Schroder et al. 2011). Other work in Australia has shown that pH management by liming was successful on Kandosols and was

associated with improved yields (Kirkham et al. 2007). There is a range of literature and case studies available on the use of lime to manage pH in similar environments (Fenton and Helyar 2007; Fageria and Baligar 2008).

To support cropping and mixed cropping practices in the Douglas Daly environment, work is required to identify cost and environmentally effective pH management strategies.

5.2.6 Sampling depth

Acidification in agricultural systems is usually observed close to the soil surface first, then deeper later (Fenton and Helyar 2007; Thomas et al. 2007). This was true for the Systems trial, with acidification occurring mainly in the top 15 cm, although three rotations also had acidification in the 15-30 cm sample zone (Table 4.13). No-tillage practices have been shown to lead to more stratified pH distribution with acidification concentrated in the top 5 cm, while cultivation treatments had a deeper zone of acidification (Conyers et al. 1996). In the Rotgut trial this effect was not observed with tillage practices having no significant differences in pH by soil depth for the period of our observation from 1991 to 2000, although this could have been true for earlier periods. The 1991-2001 Rotgut results may be due to the effect of large rainfall events in this environment, deepening the zone of acidification through the leaching of nitrates. As acidification was observed in the 15-30 cm zone by 1998, it is possible that deeper zones may have been acidified.

An appropriate sampling strategy for agricultural soil quality monitoring would compare at least two or more sample depths so that acidification starting at the surface will be detected.

5.2.7 Soil type effects

Two trials were on a 'Blain' soil (Species and Systems) and one on a 'Tippera' soil (Rotgut). Blain soils have a lower clay content than Tippera soils, but both of these soil types are described as highly weathered (Williams et al. 1985; Hill et al. 2011). Highly weathered tropical soils usually have low clay and organic matter contents and low nutrient-holding capacities and buffering capacities (Dalal and Carter 2000; Ludwig et al. 2001). Sandy soils are especially prone to agricultural acidification due to low clay and organic matter levels resulting in the leaching of acid inputs having a greater relative effect than for a heavier soil type (Helyar et al. 1990; Dolling et al. 1994). Blain soils have been identified as being particularly prone to nitrate leaching (Wetselaar 1962). Lower sorghum grain yields and sorghum N tissue contents at the early vegetative stage for sorghum following Cavalcade leys on a Blain in comparison with Tippera soil in trials at DDRF were attributed to higher rates of nitrate leaching on the Blain soil (Thiagalingam et al. 1995). In the trials reported here, it was notable that a pH decline to values less than 6 in the 0-15 cm depth occurred over a period of six or seven seasons in a number of treatments in the Systems trial on a Blain soil, compared with the Rotgut trial on a Tippera soil where a decline to less than 6 units was slower, occurring in about the eleventh season.

For the continuous sorghum rotation in the Systems trial, the decline in ox. C contents may have also reduced the buffering capacity and the cation exchange capacity (CEC) of this soil, which may have also contributed to acidification. However, there was no information available of the buffering capacity or CEC results for the soils at the three trial sites. A critical decline in the buffering capacity of soil at the Rotgut site from 1998 onwards in association with the application of fertilisers that were more acidifying than urea (DAP mixed with SOA) could explain the largest declines in pH from 1998 to 2000 in that trial. This would need to be confirmed with additional studies.

There is a need for information on the buffering capacities of agricultural soil families in the NT to assess the risk of acidification. In terms of specific monitoring for potential agricultural acidification, priority should be given to lighter soils such as Blains.

5.2.8 pH measurement methods

The variability shown for pH H_2O in comparison with pH $CaCl_2$ results in the Species trial indicated that the suitability of the pH H_2O method for monitoring the pH of similar soils in this environment needs to be examined (Figure 2.2). From comparisons of pH H_2O and pH $CaCl_2$ results it is reported that the relationship is usually linear between pH H_2O values of ~5.5 and 7 (Little 1992). Little (1992) also showed that at pH $CaCl_2$ < 5.0, the Na and Mn cations, and electrical conductivity have a strong effect on pH H_2O values but not on pH $CaCl_2$ values. However, this effect may not be relevant to our results as our pH $CaCl_2$ results were above the pH $CaCl_2$ threshold of 5 cited by Little (1992), unless a higher threshold is relevant to these particular soils. Another study had shown the role of soil conductivity on pH H_2O and pH $CaCl_2$ measurements whereby differences in readings from the two methods (ΔpH) increased with a decreasing conductivity measurement (Minasny et al. 2011). Our results, which included a narrow conductivity range, did not indicate any evidence for ΔpH values increasing with decreasing conductivity values (Figure 2.3).

A number of factors could have contributed to the variability in pH H_2O values, including the effects of highly weathered soils, changing salt concentrations and the potential that this soil has some variable charge properties (Minasny et al. 2011). Regardless of the causes, these results indicated that the use of a pH H_2O method to monitor changes in pH in this soil type provided variable results and that the pH $CaCl_2$ method was better suited for this purpose. This view was supported by a study of Queensland soils that concluded that soil pH measurement in a salt solution, either 0.01 m $CaCl_2$ or 1 m KCl, should be the preferred method compared with measurement in water because it is less affected by soil electrolyte concentration and provided a more consistent measurement (Minasny et al. 2011). However, as conclusions in this report were based on samples from a single experimental site, data from more seasons and sites comparing the pH H_2O and pH $CaCl_2$ methods will be required to evaluate this further.

Further studies need to be undertaken to establish if the pH $CaCl_2$ method is more sensitive and is therefore more appropriate than the pH H_2O method for agricultural soil quality monitoring in the NT.

5.2.9 Land clearance effects

The clearance of native vegetation for pasture or cropping has been associated with declines in pH in areas of Australia (Williams and Chartres 1991; Dolling and Porter 1994; Moody and Aitken 1997; Noble et al. 1998; Rasiah et al. 2004). Although it is not possible to separate the effects of clearing from those of agricultural management, soil pH comparisons of uncleared areas were included in the Species and Rotgut trials.

Results from an uncleared area in comparison with the three buffel and Wynn cassia fields in the Species trial found that the bush area had a higher pH $CaCl_2$ for samples collected in the early wet season (2010) but not after the wet season (2011) (Tables 2.13 and 2.14). Although a small number of samples were compared, it was possible to cross reference the values used in this comparison. The pH H_2O values for the bush area at 6.6 and 6.7 for the 0-15 and 15-30 cm zones, respectively in May 2011 were similar with pH (acid based indicator method) values of 6.5 for two profiles for samples between 3 and 35 cm deep in July 2007 about 650 m from this site (Raupach and Tucker 1959; NRETAS 2011) (Appendix 1). The shallower top 3 cm sandy profile had a pH of 6.0. The pH H_2O values for the buffel fields were also similar to the mean values for the larger sample of species fields made in 2010 (Tables 2.9 and 2.13). Thus comparison with these other data sources provided some additional confidence that there was a lower pH in the buffel fields than in the bush area for the pre-wet season 2010 sample.

However, repeat post-wet season sampling in May 2011 indicated no pH differences between bush and buffel (Table 2.14). A comparison with pH values (acid based indicator method) of 6.7 from profiles in the top 30 and 40 cm of two soil pits from the Species trial in August 1979 (NRETAS 2011) (Appendix 1) also indicated little evidence for long-term pH change, as the May 2011 pH H_2O values of 7.0 and 6.97 for the 0-

15 and 15-30 cm sample depths were similar to those recorded in 1979. It is however, notable that the 1979 samples were taken approximately 17 years after the land was cleared.

The seasonal pasture to bush pH comparisons appear to indicate differing pH buffering dynamics between the two land uses rather than just a differing pH. The pH values for the bush area at the 0-15 cm depth were the same or very similar between the 2010 and 2011 sample dates (5.93 and 5.93 pH $CaCl_2$, 6.60 and 6.63 pH H_2O) while the pH values at both depths increased in the buffel fields from 2010 to 2011. In some long-term pastoral and cropping studies in Australia, the C cycle has been identified as having a larger contribution to acidification than the N cycle due to declines in soil C reducing the buffering capacity of the soil (Ridley et al. 1990b; Slattery et al. 1998). There was some limited evidence for greater ox. C levels in the 0-15 cm zone under bush than in buffel fields but not for the 15-30 cm zone for the 2010 samples. More intensive sampling of these areas may be required to determine if differing vertical soil C distributions contribute to differing buffering capacities and therefore differing pH responses to seasonal factors.

For the Rotgut trial, additional urea treatments in 1996 showed that the use of additional N in cropping led to a lower pH than in uncleared land; however, pH values between the nil additional nt and ct treatments did not differ from those of the uncleared bush (Table 3.10). The pH values from a soil description pit in 1981 (pH 6.0) in uncleared bush (NRETAS 2011) indicated that the 1996 bush results (pH 6.3) were representative. However, as these results were from one time point in a single year, a more intensive investigation may be required to substantiate these particular findings.

The sampling of uncleared areas for comparison with those under agricultural management may provide useful comparisons, although sampling strategies need to employ adequate replication for results to be qualitatively useful.

5.3 RECOMMENDATIONS

The following recommendations are suggested for the effective use of soil C to monitor soil quality in agricultural soils in the NT:

1. Evaluate the use of more sensitive soil C measures than the modified W-B method in conjunction with the use of a method that will measure the total amount of soil C.

2. Sample areas with documented declines or increases in soil C concentrations (such as that in the Systems trial) in order to understand how these concentrations may change with time. This knowledge is required to better understand the long-term change and agricultural effects on soil C concentrations in agricultural land.

3. Determine the ongoing effect of nitrogenous fertilisers on soil C concentrations. A strong effect of urea application on soil ox. C values was found in samples collected during the wet season. Work is required to establish if these effects continue through time, such as during the following dry season.

4. Make conclusions on soil C values from multiple time-points.

5. Identity the most environmentally stable periods for sample collection due to large seasonal effects on soil C values.

The following recommendations are suggested for the effective use of soil pH to monitor soil quality in agricultural soils in the NT:

1. Improve the understanding of seasonal and temporal variability in pH values. Quantify the extent of variation so that appropriate sampling strategies and result interpretations are used. Due to the

variable results observed in our study, it is also recommended that conclusions should be based on results from multiple time-points only.

2. Establish if the pH $CaCl_2$ method is more sensitive and so is more appropriate than the pH H_2O method for agricultural soil quality monitoring in the NT.

3. Resample areas with documented historical agricultural acidification (such as those in the Rotgut and Systems trials) in order to understand if acidified areas correct with time, the extent of any correction and if effects were permanent.

4. Determine the relative effects of fertilisers used in crops and ley pastures on acidification.

5. Determine if acidification is occurring in association with continuous cropping and ley pasture rotations on commercial farms.

6. Identify methods to mitigate the effects of acidification and prevent future acidification.

7. Determine the buffering capacity of common agricultural soils in the NT to predict the risk of acidification.

8. Identify environmentally and cost-effective pH management strategies for use in mixed cropping and continuous cropping rotations.

The following recommendations are suggested for soil quality monitoring in agricultural soils in the NT:

1. Develop a database of results from trials and surveys on agricultural land to evaluate existing analyses.

2. Develop a set of agricultural soil quality indicators, including soil pH and soil C that include recommended analysis method and sampling protocols.

3. Develop a soil quality monitoring program based on demonstrating the value of monitoring and the use of designated monitoring sites on government and prominent private farms.

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APPENDICES

APPENDIX 1: SPECIES TRIAL SITE AND SOIL DESCRIPTIONS

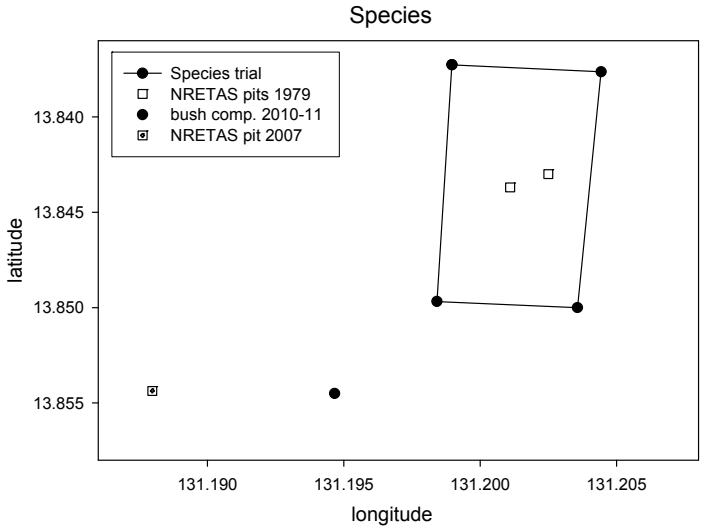

Figure A 1.1. Species trial location in relation two soil description pits made in 1979 (NRETAS 2011) and one pit made in 2007 (NRETAS 2011), also indicated is the centre of the site of soil sampling in three areas in uncleared bush in 2010 and 2011 for comparisons with the Species trial

Table A 1.1. Information on profiles, soil fabric, pedality grade, pH (Raupach and Tucker 1959) and texture grade from two soils description pits (DDES1B5 and DDES1B6)) sampled on the 30/08/1979 (NRETAS 2011)

		Profiles,(m)	Fabric	Pedality grade	pH	Texture grade
DDES1B5	Ap1	0-0.1	earthy	massive	6.7	loamy sand
	Ap2	0.1-0.3	earthy	massive	6.7	loamy sand
	B1	0.3-0.7	earthy	massive	6.7	sandy clay loam
	B2	0.7-1.5	earthy	massive	6.7	light clay
DDES1B6						
	A1	0-0.1	earthy	massive	6.7	sandy loam
	A3	0.1-0.4	earthy	massive	6.7	sandy loam
	B1	0.4-0.7	earthy	massive	6.7	sandy clay loam
	B2	0.7-1.5	earthy	massive	6.7	light clay

Table A 1.2. Information on the profiles, soil fabric, pedality grade, pH (Raupach and Tucker 1959) and texture grade from one soils description pits (DDSMT10) sampled on the 11/07/2007 (NRETAS 2011)

	Profiles (m)	Fabric	Pedality grade	pH	Texture grade
A11	0-0.03	sandy	single grain	6	loamy sand
A12	0.03-0.13	earthy	massive	6.5	sandy loam
B21	0.13-0.35	earthy	massive	6.5	sandy clay loam
B22	0.35-1.25	earthy	massive	6.5	light clay
B23	1.25-1.35	-	-	7	light clay

APPENDIX 2: SPECIES TRIAL PRE 2010 FIELD VALUES

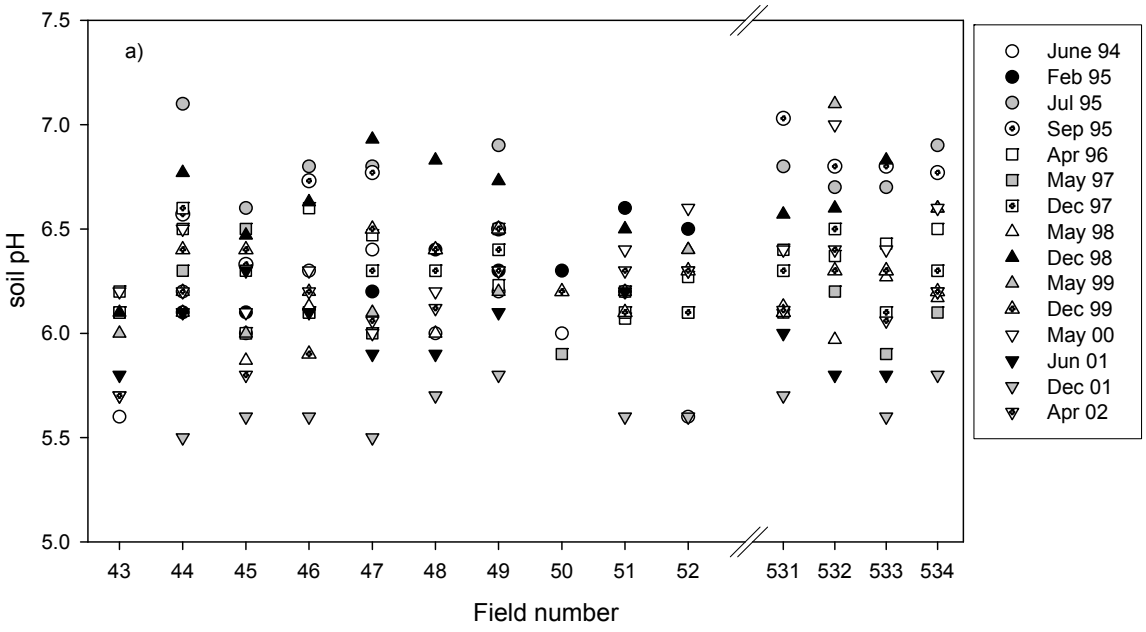

Figure A 2.1. a) Soil pH and b) Oxidisable C values for 0-15 cm samples for fields sampled more than once in the Species trial from 1994 to 2002

APPENDIX 3: SPECIES TRIAL LONG TERM VALUES FOR SEVEN FIELDS

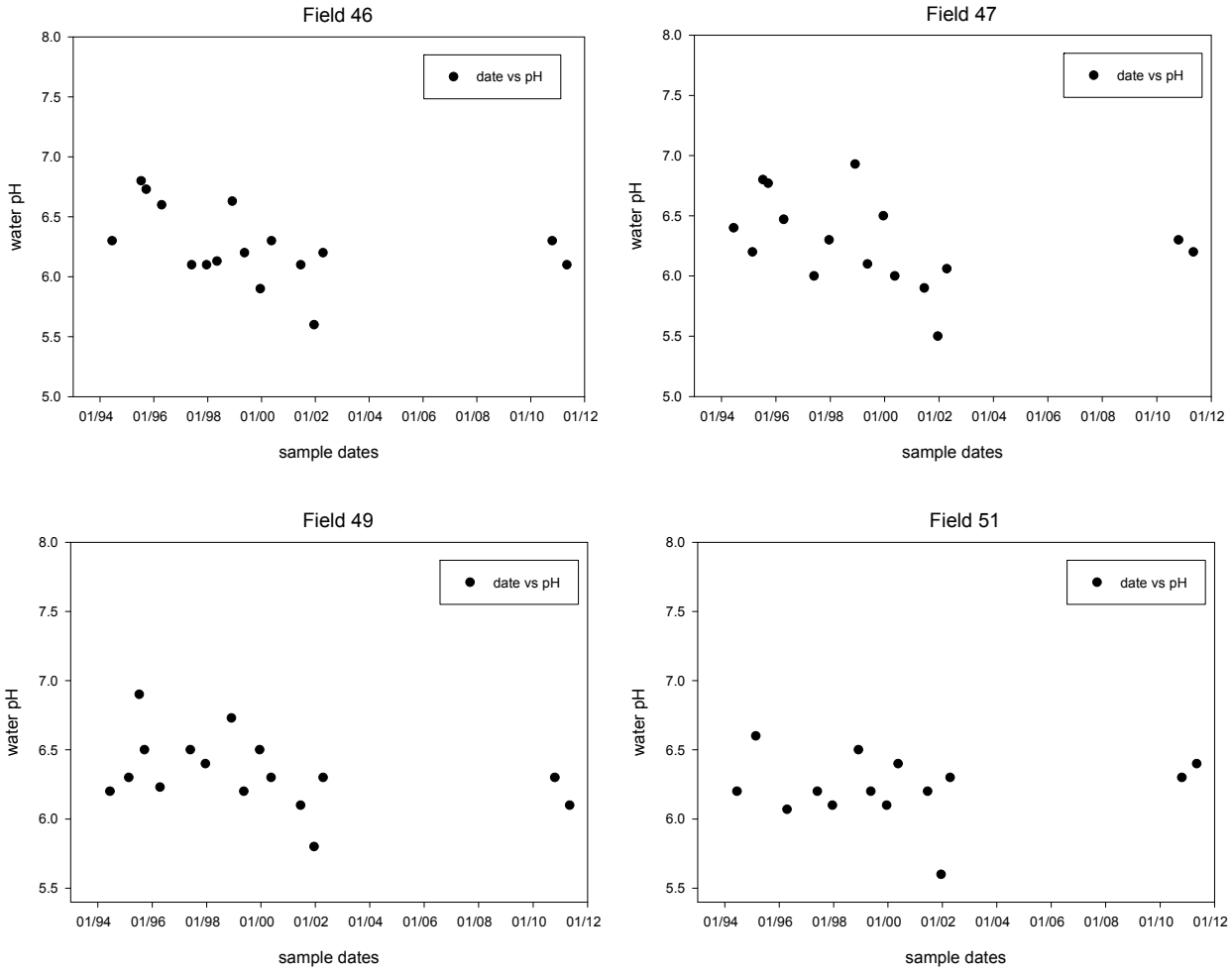

Figure A 3.1. Water method pH plots for fields 46, 47, 49 and 51 showing all 0-15 cm samples for samples from 1994 to 2011

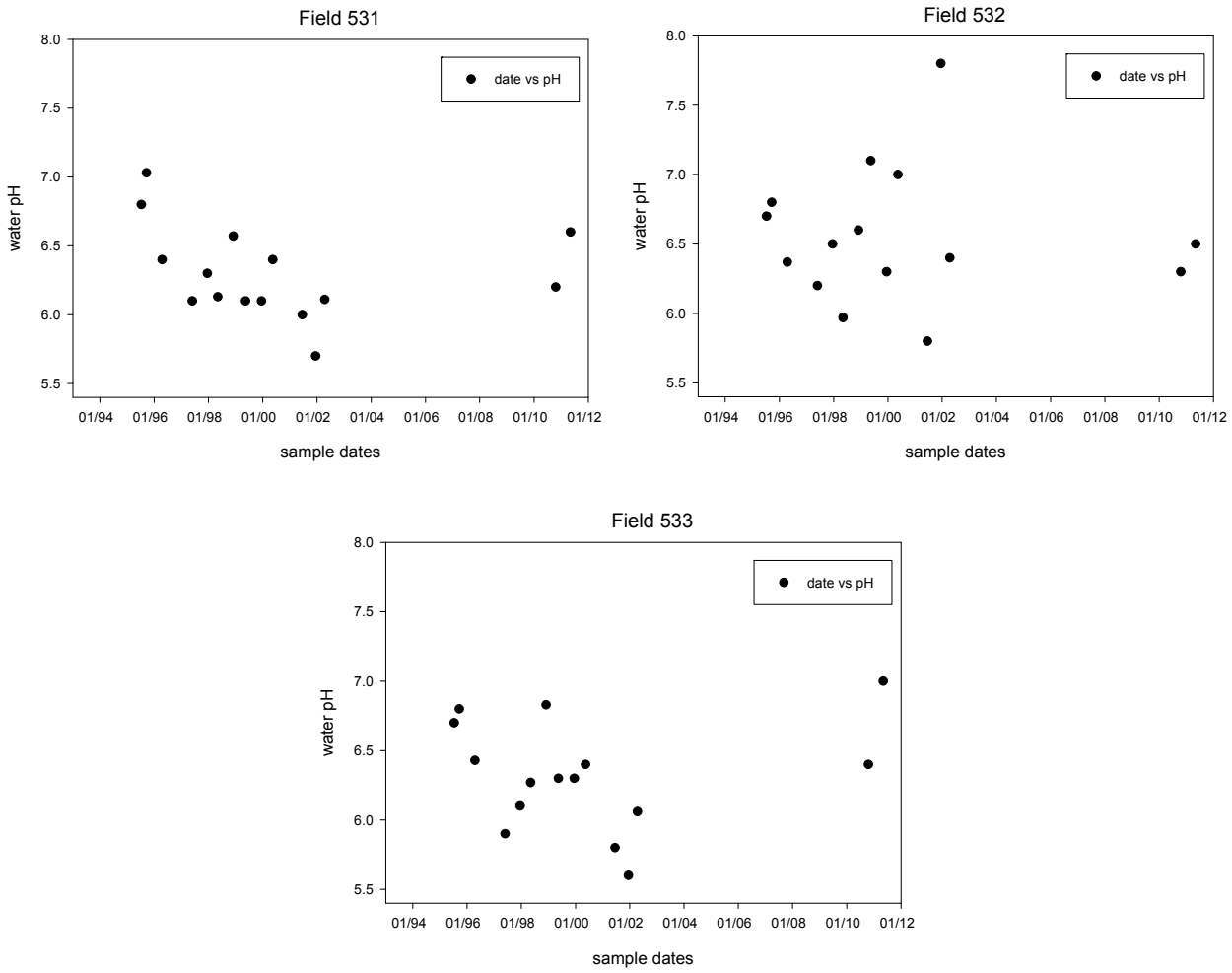

Figure A 3.2. Water method pH plots for fields 531, 532 and 533 showing all 0-15 cm samples for samples from 1994 to 2011

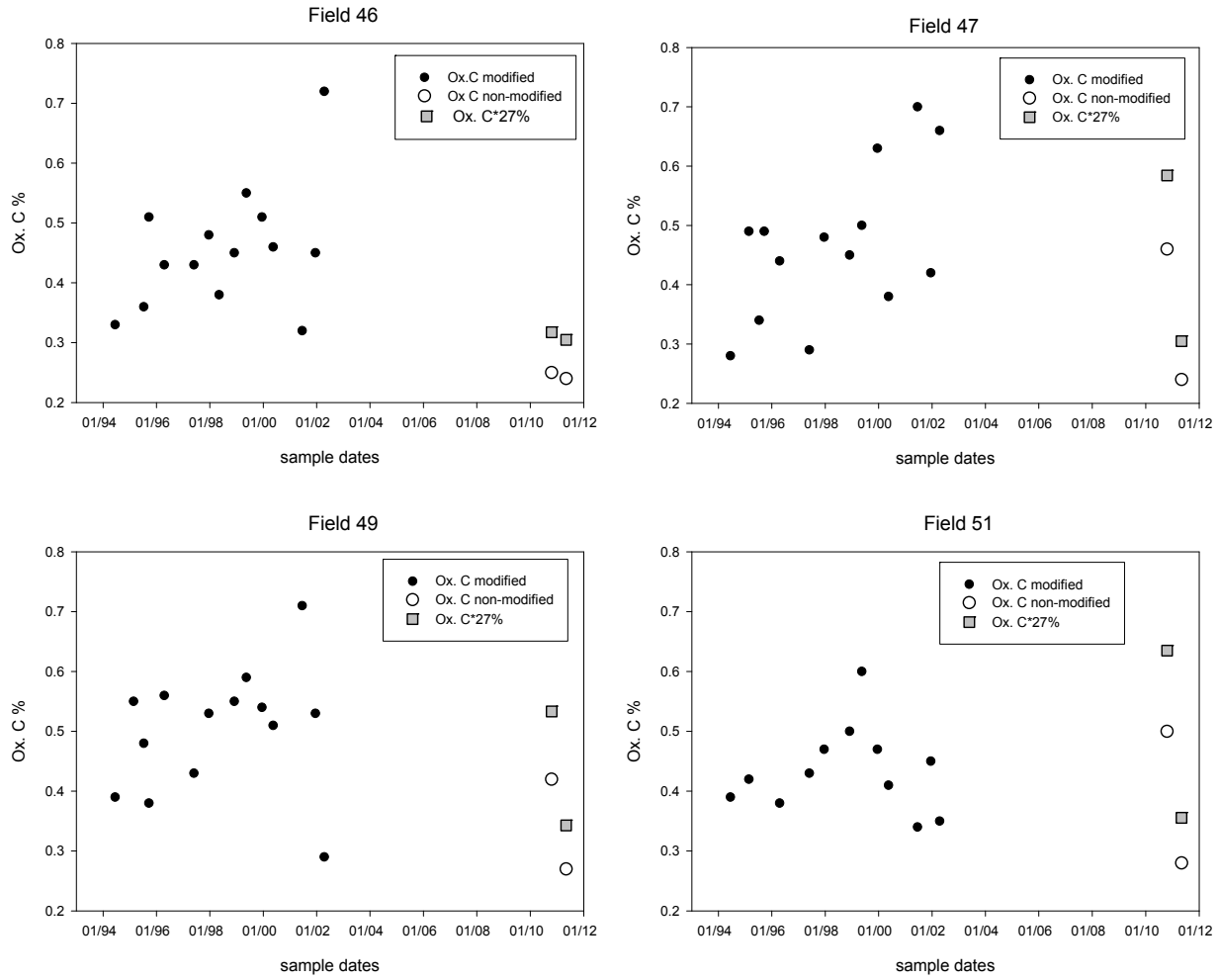

Figure A 3.3. Oxidisable C (ox. C %) over time for fields 46, 47, 49 and 51 showing all 0-15 cm samples for samples from 1994 to 2011, the 2010 and 2011 results from a differing W-B method are indicated as well as values being corrected (*27%) also being separately shown

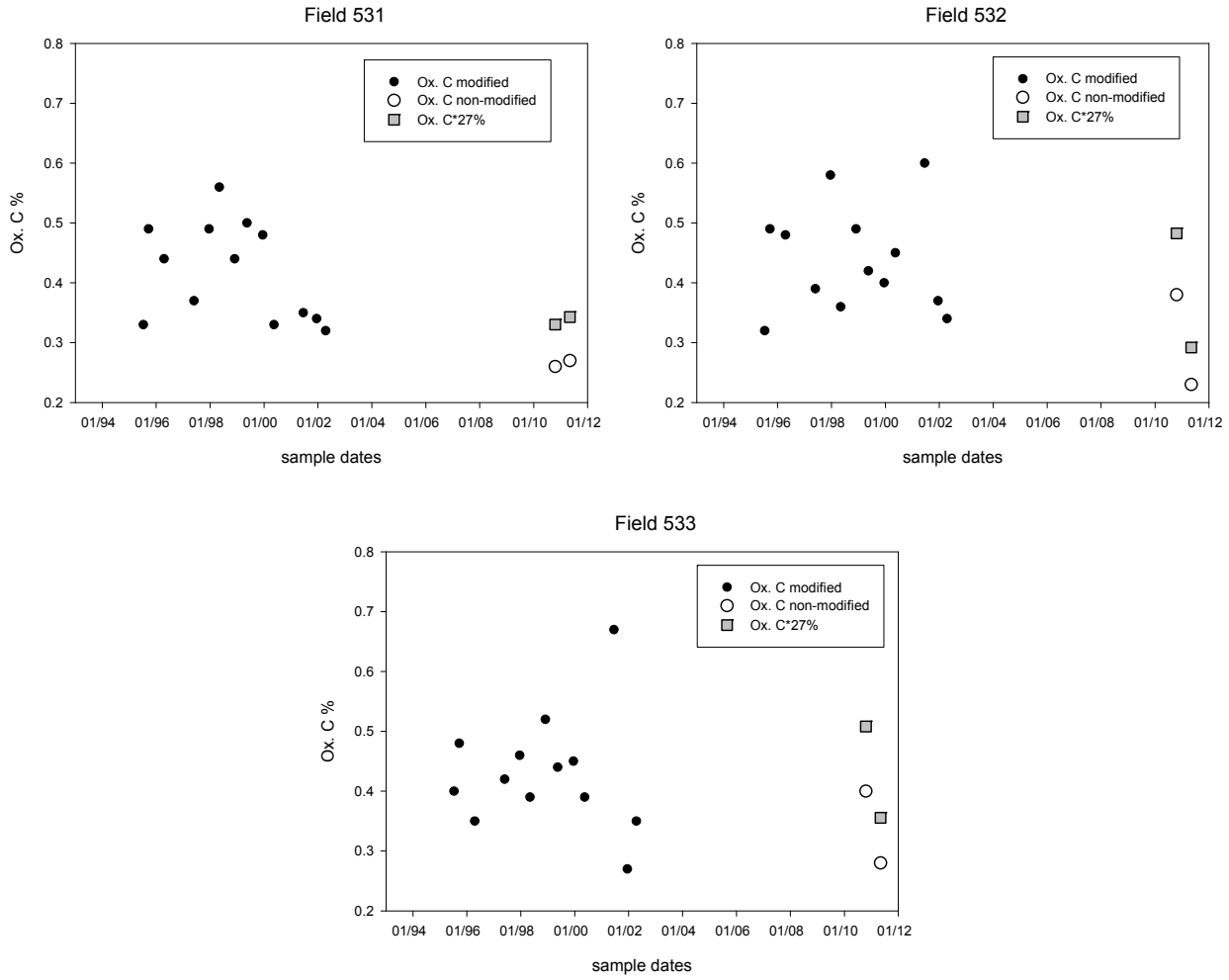

Figure A 3.4. Oxidisable C (ox. C %) over time for fields 531, 532 and 533 showing all 0-15 cm samples for samples from 1994 to 2011, the 2010 and 2011 results from a differing W-B method are indicated as well as values being corrected (*27%) also being separately shown

APPENDIX 4: ROTGUT TRIAL SITE AND SOIL DESCRIPTIONS

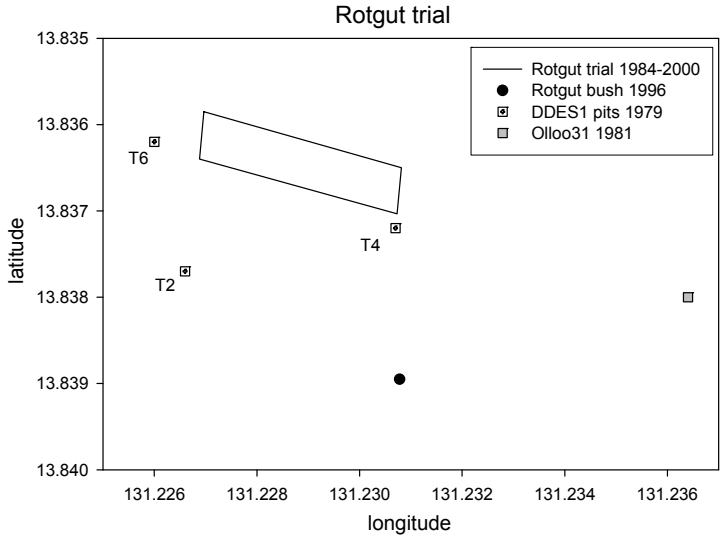

Figure A 4.1. Rotgut trial location in relation to three soil description pits made in 1979 with individual tags (T2, T4, T6) for the DDES1 series (NRETAS 2011) and one pit made in 1981 (Olloo 31) (NRETAS 2011), also indicated is the centre of the site of soil sampling in three areas in uncleared bush in 1996 for comparisons with the Rotgut trial

Table A 4.1. Information on profiles, soil fabric, pedality grade, pH (Raupach and Tucker 1959) and texture grade from four soil description pits (NRETAS 2011) adjacent to the Rotgut trial as shown in Figure A 4.1

		Profiles, (m)	Fabric	Pedality grade	pH	Texture grade
DDES1T2	A1	0-0.2	earthy	massive	6.0	clay loam
28/8/1979	A3	0.2-0.4	earthy	massive	6.5	clay loam
	B11	0.4-0.9	earthy	massive	7	light clay
	B12	0.9-1.1	earthy	massive	7	light clay
	B21	1.1-1.3	earthy	massive	7	light medium clay
DDES1T4						
28/8/1979	A1	0-0.2	earthy	massive	6.5	clay loam
	B1	0.2-0.4	earthy	massive	6.5	light clay
	B21	0.4-1.3	earthy	massive	6.0	light clay
	B22	1.3-1.5	earthy	massive	6.0	light medium clay
DDES1T6						
29/8/1979	A1	0-0.2	earthy	massive	6.0	sandy loam
	B1	0.2-1.2	earthy	massive	6.5	light clay
	B2	1.2-1.5	earthy	massive	7.0	light clay
Olloo 31						
15/10/1981	A1	0-0.1	earthy	massive	6.0	sandy clay loam
	A3	0.1-0.2	earthy	massive	6.0	sandy clay loam
	B1	0.2-0.3	earthy	massive	6.0	clay loam
	B21	0.3-0.75	earthy	massive	6.0	light clay
	B22	0.75-1.5	earthy	massive	6.0	clay loam

From the soil descriptions carried out across the Tippera experimental site in 1979 and 1981 Lucas (1984) identified four general soil types(Table A 4.2), as part of the description. pH values were provided for each soil horizon. The pH values were possibly from the acid based indicator method of Raupach and Tucker (1959). The Rotgut trial was located in a bay (DPP6) and described as a Tippera clay loam by Lucas (1984).

Table A 4.2. pH values for soil horizons for each of the four classes of Tippera soils identified by Lucas (1984) at the Tippera experimental site, Douglas Daly Research Farm. Sample dates for this study were in 1979 and 1982.

Tippera clay loam	Tippera sandy clay loam	Tippera sandy phase	Blain-Tippera intergrade
Horizon pH	Horizon pH	Horizon pH	Horizon pH
0-10 cm 7.0	0-10 cm 7.0	0-10 cm 7.0	0-3 cm 6.8
10-20 cm 7.0	10-20 cm 7.0	10-20 cm 7.0	3-20 cm 6.8
20-30 cm 6.8	20-130 cm 6.8	20-60 cm 6.8	20-30 cm 6.8
30-60 cm 6.8		60-150 cm 6.5	30-45 cm 6.5
60-150 cm 6.8			45-150 cm 6.5

During the dry season in 1986 a series of samples were collected for analyses from the SMP area of the Tippera experimental site (Table A 4.3). Lucas (1984) had identified: SMP bay 1 as Tippera sandy phase; SMP bay 2 as Tippera sandy clay loam; SMP bays 3, 4 ,5 and 6 as Tippera clay loam; and SMP bay 7 as a Blain-Tippera intergrade that was mainly Blain. SMP bays 3, 4 ,5 and 6 were part of the same continuous area of Tippera clay loam that contained the Rotgut trial in bay DPP 6.

Table A 4.3. pH values for three soil depths collected on 29 July 1986 by Neville S. Gould, John England Building Crops Section, Darwin (unpublished results of soil analyses sourced from Berrimah Agricultural Research Centre, Chemistry Section, records) from the seven SMP bays described by Lucas (1984). Ten separate cores were collected and bulked for each sample. Tippera clay loam bays highlighted in grey. The pH method was the water method as described in section 1.4.

SMP Bay no.	Land use	Land use	Sample zone		
	1984-85	1985-86	0-10 cm	10-15 cm	15-20 cm
SMP Bay 1	Maize	Soybean	6.0	6.3	6.4
SMP Bay 2	Maize	Soybean	6.1	6.0	6.2
SMP Bay 3	Maize	Soybean	6.3	6.2	6.3
SMP Bay 4	Soybean	Mungbean	6.0	6.5	6.3
SMP Bay 5	Maize	Soybean	6.7	6.7	6.6
SMP Bay 6	Uncleared bush	Uncleared bush	7.3	6.9	7.1
SMP Bay 7	Verano pasture	Verano pasture	6.3	7.9	6.7

APPENDIX 5: TIPPERA EXPERIMENTAL SITE BULK DENSITY VALUES

Table A 5.1. Bulk density values (BD) collected at six depths from the Tippera experimental block in the 1984-85 and 1985-86 seasons at DDRF (M. Bennett, DPIF, unpublished results).

Sample depth, cm	1984-85 BD g/cm^3	1985-86 BD g/cm^3	average BD g/cm^3
10	1.66	1.58	1.620
20	1.68	1.69	1.685
40	1.56	1.67	1.615
60	1.53	1.60	1.565
80	1.50	1.60	1.550
100	1.47	1.60	1.535

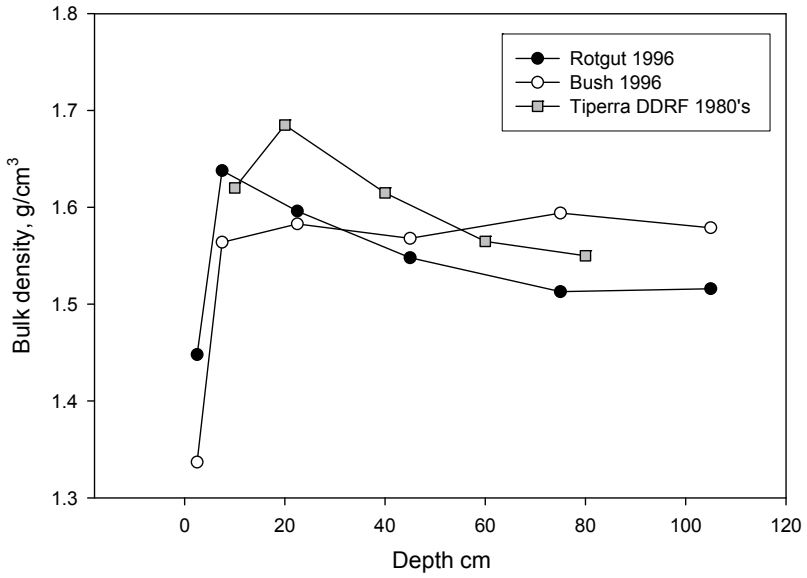

Figure A 5.1. Bulk density values by sample depth for: the bush area adjacent to the Rotgut trial sampled in 1996; average bulk density values for both tillage treatments in the Rotgut trial sampled in 1996; and mean values for samples from the Tippera experimental site collected in 1985 and 1986. Note, Rotgut and bush samples are presented for the midpoint of each sample zone.

APPENDIX 6: SYSTEMS TRIAL PLOTS OF TREATMENT MEANS

Plots of data from consecutive samples for informing model selection for treatment comparisons

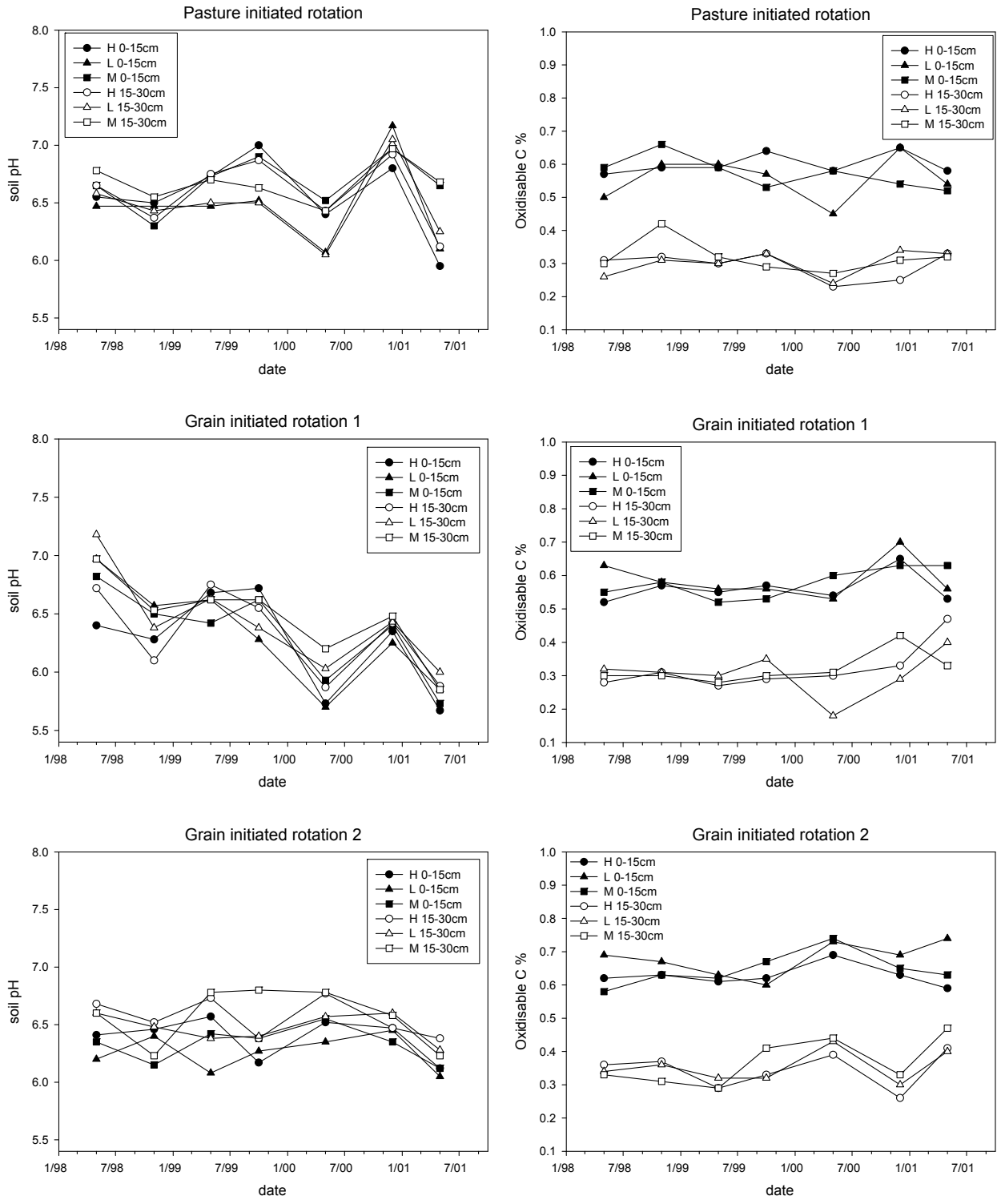

Figure A 6.1. Grazing treatment (high (H), medium (M) and low (L) densities) means for the three ley rotations treatments (as labelled) for soil pH (left plots) and oxidisable C % (plots on the right) values for consecutive sample dates for 0-15 and 15-30 cm sample zones (November 1998 to May 2001).

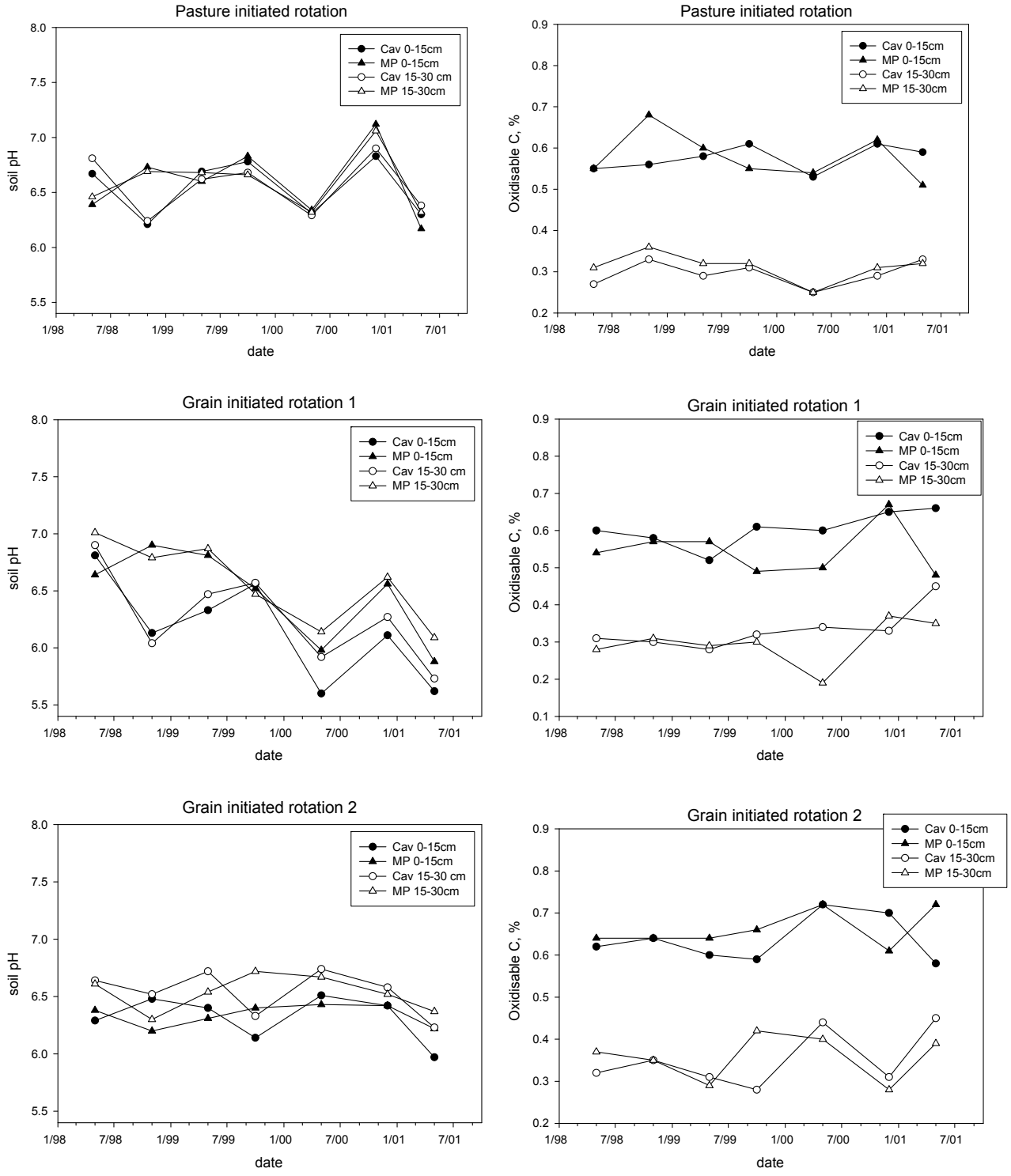

Figure A 6.2. Ley pasture treatment (Cav., Cavalcade, MP, mixed pasture) means for the three ley rotations treatments (as labelled) for soil pH (left plots) and Oxidisable C % (plots on the right) values for consecutive sample dates for 0-15 and 15-30 cm sample zones (November 1998 to May 2001).

APPENDIX 7: SYSTEMS TRIAL pH AND OXIDISABLE C VALUES OVER TIME

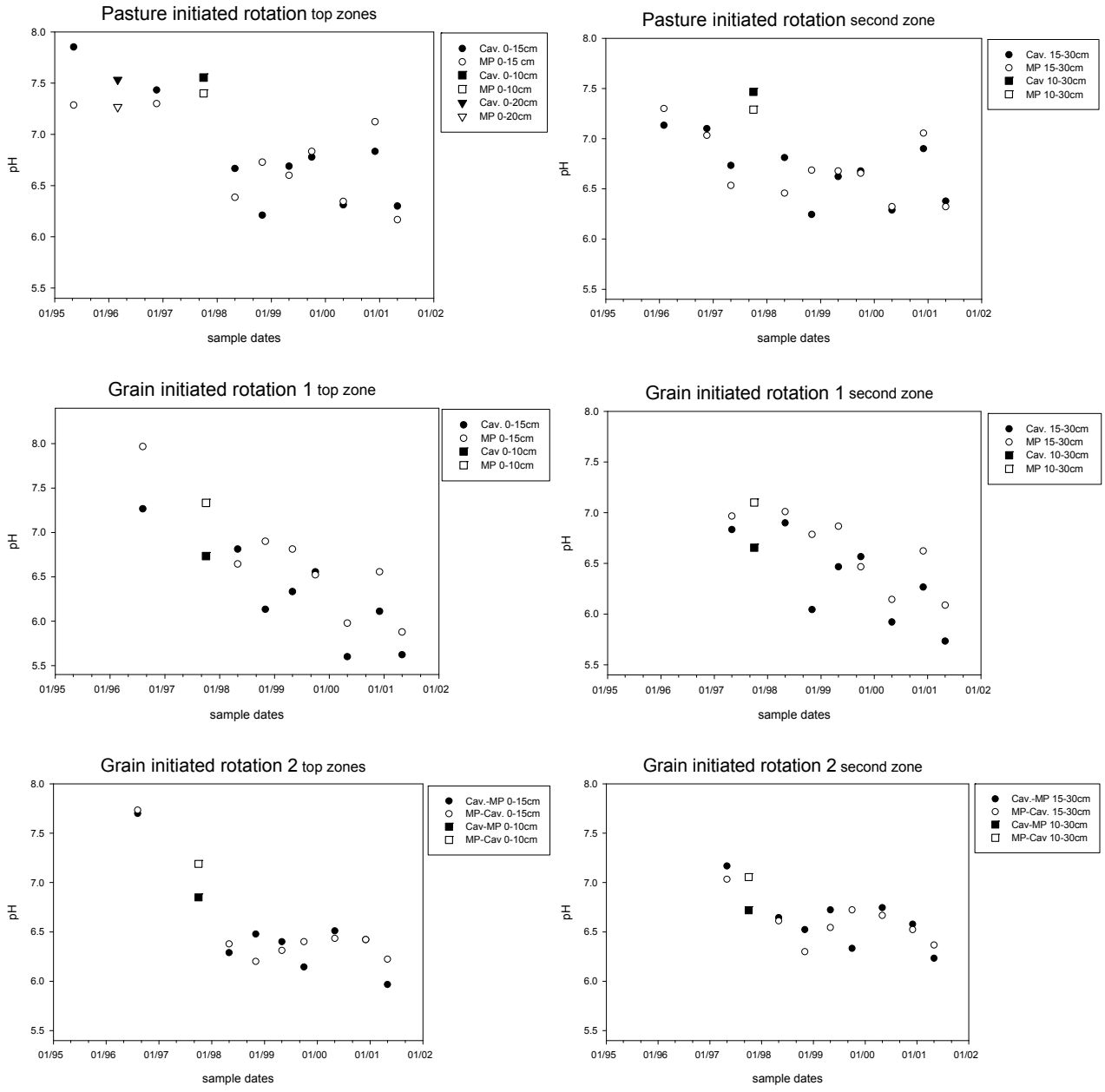

Figure A 7.1. Soil pH the top (plots on the left) and second (plots on the right) sample zones for sample dates when > 5 cm corer was used for the top zone from samples from the three ley rotations treatments (as labelled) presented by ley pasture treatment means of Cavalcade (Cav.) and mixed pasture (MP). Samples depths are indicated in each plot

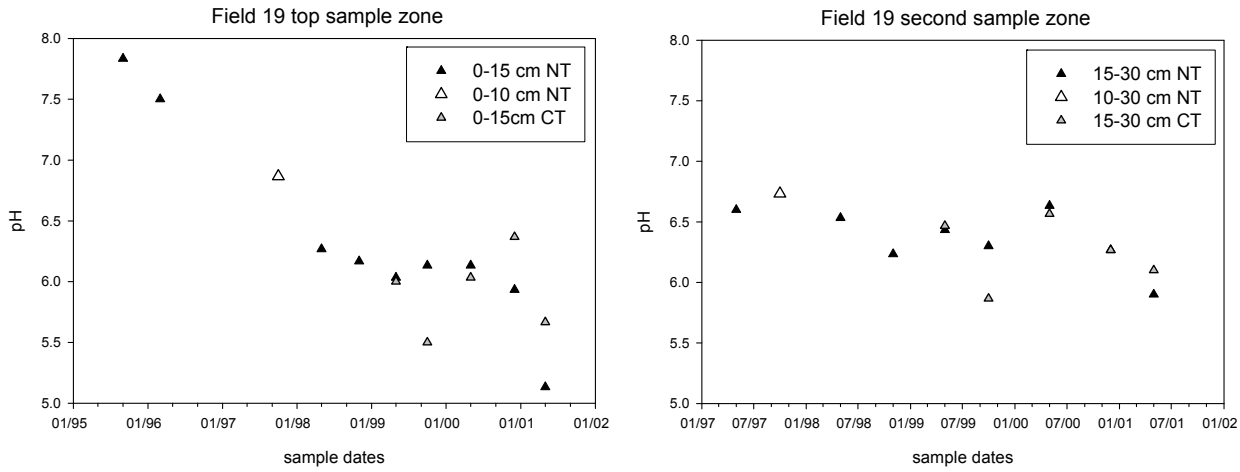

Figure A 7.2. Soil pH the top (left plot) and second (right plot) sample zones for sample dates when > 5 cm corer was used for the top zone from samples from Field 19 which had sorghum grown each wet season, no-tillage (nt) and conventional tillage (ct) treatment means from 1999 to 2001 presented separately. Samples depths are indicated in each plot.

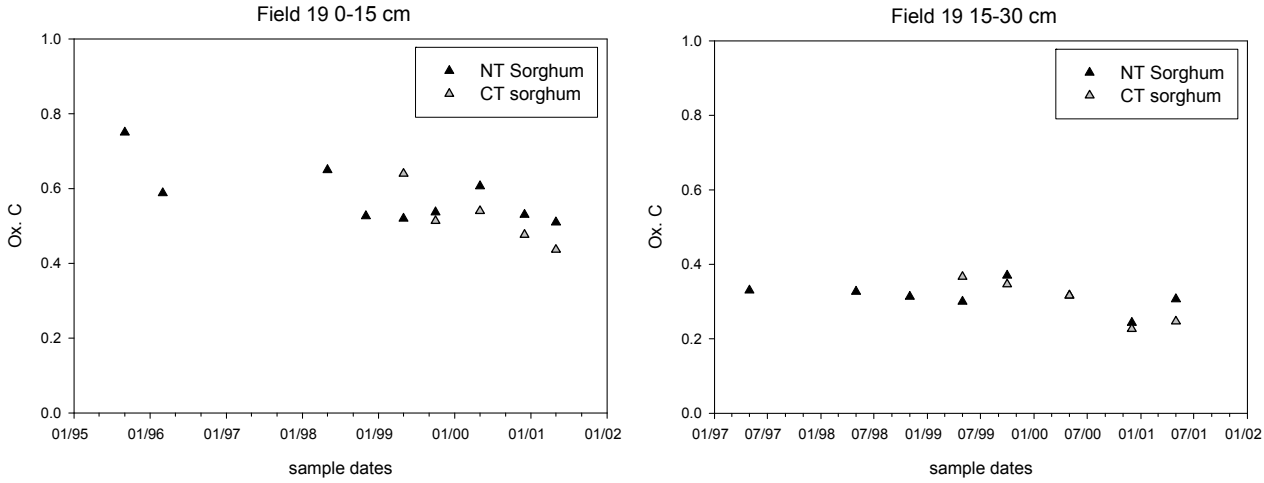

Figure A 7.3. Soil oxidisable C (ox. C %) concentrations for 0-15 cm (left plot) and 15-30 cm (right plot) samples from Field 19 which had sorghum grown each wet season, no-tillage (nt) and conventional tillage (ct) treatment means from 1999 to 2001 presented separately

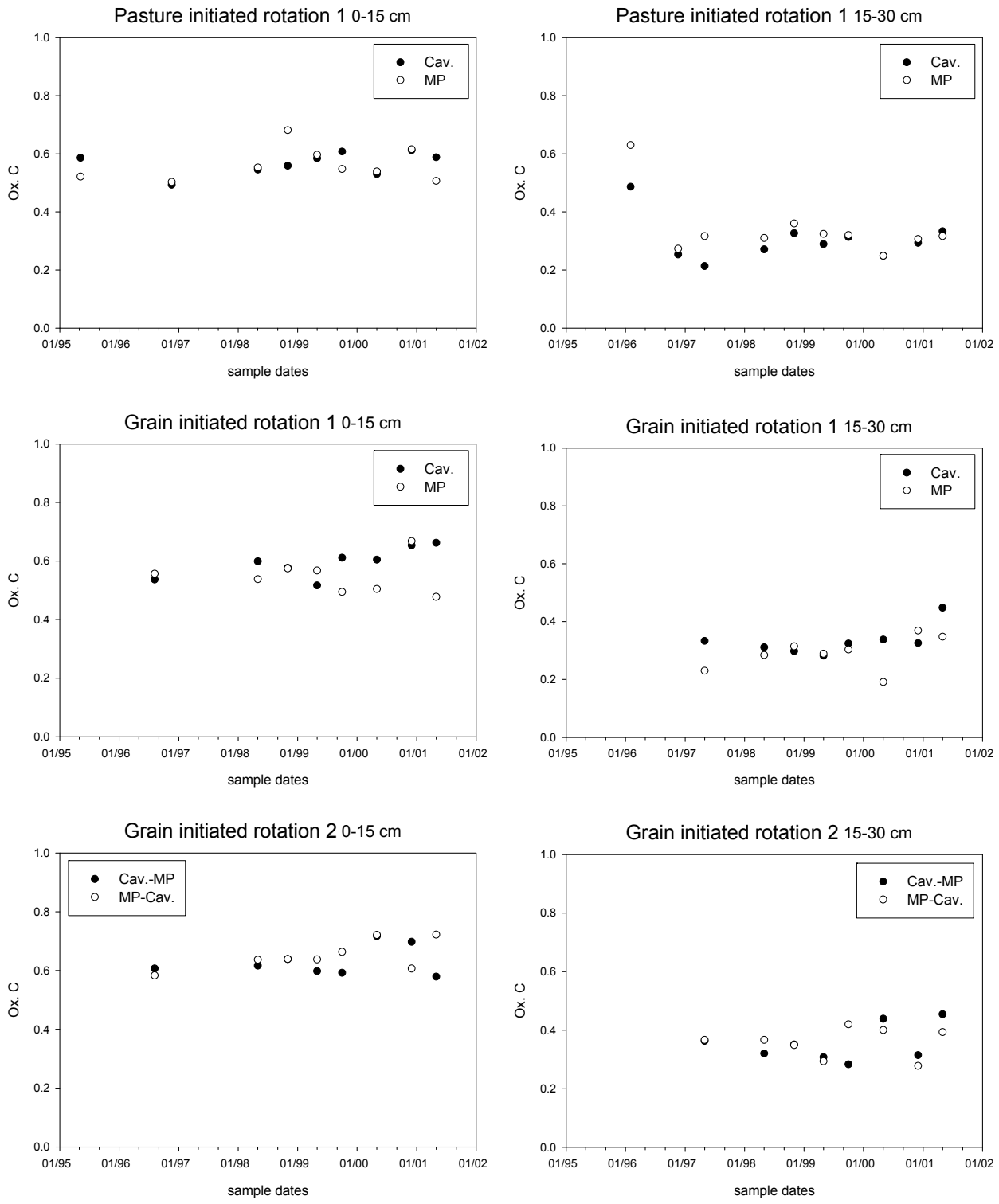

Figure A 7.4. Soil oxidisable C (ox. C) % concentrations for 0-15 cm (plots on the left) and 15-30 cm (plots on the right) samples from the three ley rotations treatments (as labelled) presented by ley pasture treatment means of Cavalcade (Cav.) and mixed pasture (MP)