LONG-TERM EFFECTS OF RESIDUE MANAGEMENT ON SOIL FERTILITY INDICATORS, NUTRIENT UPTAKE AND WHEAT GRAIN YIELD

by

PALO FRANCIS LOKE

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Department of Soil, Crop and Climate Sciences
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Supervisor: Mrs E Kotzé

Co-supervisor: Prof CC Du Preez

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DECLARATION

I declare that the dissertation hereby handed in for the qualification at the University of the Free State, is my own independent work and that I have not previously submitted the same work for a qualification at/in another University/faculty. I furthermore cede copyright of the dissertation in favour of the University of the Free State.

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ABSTRACT

Long-term effects of residue management on soil fertility indicators, nutrient uptake and wheat grain yield

Farmers have largely depended on intensive soil cultivation to reduce nutrient stratification and therefore distribute nutrients homogeneously across the root zone for optimum crop productivity. This attempt however, has led to serious soil organic matter degradation and nutrient outflows. Consequently, food production for the increasingly growing world population was severely threatened. Crop residues as a source of organic matter and nutrients, when properly managed, can restore or improve soil fertility, and hence crop yields.

The different residue management practices on some soil fertility indicators have been examined since 1979 in a long-term wheat trial at the ARC-Small Grain Institute near Bethlehem in the Eastern Free State on an Avalon soil. The observations established in 1999 indicated that soil nutrient and organic matter stratification still continues, therefore it was found necessary to further investigate the effects of these residue management practices on some soil fertility indicators, nutrient uptake and wheat grain yield. The applied field treatments include two methods of straw disposal (unburned and burned), three methods of tillage (no-tillage, stubble mulch and ploughing) and two methods of weeding (chemical and mechanical). Soil samples were collected in 2010 at various depths *viz.* 0-50, 50-100, 100-150, 150-250, 250-350 and 350-450 mm and analyzed for organic C, total N and total S as organic matter indices, pH, some macronutrients (P, K, Ca, Mg and Na) and CEC, as well as some micronutrients (Cu, Fe, Mn and Zn). At mid-shooting stage, plants were sampled in each treatment plot, oven-dried at 68 ºC, weighed, milled and analyzed for N, S, P, K, Ca, Mg, Na, Cu, Fe, Mn, and Zn. The grain yield data of wheat for the 26 years were supplied by the ARC-Small Grain Institute for use as a supplement to the soil data.

The methods of straw disposal and tillage had variable influences on soil organic matter indices. Unburned straw increased total N and S, but reduced organic C when compared to the burned straw. No-tillage increased organic C only in the 0-50 mm soil depth when compared to stubble mulch and ploughing. No-tillage and stubble mulch resulted in a higher total N to a soil depth of 450 mm relative to mouldboard ploughing. Ploughing on the other hand, and to some extent stubble mulch, increased total S more than no-tillage in the upper 250 mm soil depth. Mechanical weeding enhanced these indices to 450 mm soil depth as opposed to chemical weeding. No-tillage and to some extent stubble mulch suppressed acidification in the upper 100 mm and lower 350-450 mm soil depths. Mechanical weeding also increased soil pH when compared to chemical weeding. No-tillage combined with either chemical weeding or straw burning suppressed acidification in the surface soil, whereas mechanical weeding combined with either no-tillage or mouldboard ploughing retarded acidification in the subsoil. The concentrations of P, K, Mg, Mn and Zn were higher in the burned treatments than in the unburned plots. The reverse was observed with Ca, Na and Cu. In contrast, mouldboard ploughing, and to some extent stubble mulch, resulted in an accumulation of Cu in the upper 100 mm soil depth when no-tillage served as a reference. Chemical weeding enhanced P, K, Mg, Na and CEC, but resulted in lower Ca, Cu, Fe, Mn and Zn contents when compared to mechanical weeding.

The applied management practices were also tested on nutrient uptake and grain yield. Although not always significant, the burned straw increased nutrient uptake, but resulted in a lower wheat grain yield when compared to unburned straw. Despite the beneficial effects of no-tillage and stubble mulch on the fertility status of this Avalon soil, higher nutrient uptake and grain yield were perceived under mouldboard ploughing. Mechanical weeding also enhanced the uptake of most of the studied nutrients relative to chemical weeding. Mouldboard ploughing combined with either unburned straw or chemical weeding increased nutrient uptake and wheat grain yield. However, irrespective of the applied field treatments, nutrient concentrations in oat straw were below optimum levels, and possibly plants were already suffering acute nutrient deficiencies.

Keywords: Nutrient uptake, residue management, soil fertility, wheat grain yield

UITTREKSEL

Lang-termyn effekte van oesreste bestuur op grondvrugbaarheids indikatore, voedingstofopname en koringgraan opbrengste

Boere het grootliks staatgemaak op intensiewe grondbewerking om voedingstof-stratifikasie te verminder en dus voedingstowwe homogeen te versprei regoor die wortelsone vir optimum gewasproduktiwiteit. Hierdie poging het egter gelei tot ernstige grond organiese materiaal degradasie sowel as voedingstofverliese. Gevolglik is voedselproduksie ernstig bedreig vir ‘n toenemend groeiende wêreld populasie. Gewasreste is ‘n bron van organiese material en voedingstowwe, en indien dit reg bestuur word kan dit grondvrugbaarheid herstel of verbeter, en dus ook gewasopbrengste.

Die verskillende oesreste-bestuurspraktyke op sekere vrugbaarheidsindikatore word al vanaf 1979 bestudeer in ‘n lang-termyn koringproef by die LNR-Kleingraan Instituut naby Bethlehem in die Oos-Vrystaat op ‘n Avalon grond. Die observasies wat in 1999 gemaak is, dui aan dat grondvoedingstof en organiese materiaal stratifikasie steeds gebeur, dus was dit nodig om verdere ondersoek te doen op die effekte van hierdie oesrestebestuurspraktyke op sekere grondvrugbaarheids-indikatore, voedingstofopname en graanopbrengste van koring. Die toegepaste behandelings sluit in twee metodes van oesreste wegdoening (nie-brand en brand), drie metodes van bewerking (geen-bewerking, deklaagbewerking en konvensionele bewerking) en twee metodes van onkruidbeheer (chemies en meganies). Grondmonsters was geneem in 2010 op verskeie dieptes nl. 0-50, 50-100, 100-150, 150-250, 250-350 en 350-450 mm en geanaliseer vir organiese C, totale N en totale S as organiese materiaal indikatore, pH, sommige makrovoedingstowwe (P, K, Ca, Mg en Na) en KUK, sowel as sommige mikrovoedingstowwe (Cu, Fe, Mn en Zn). By mid-stamverlenging stadium is plantmonsters geneem in elke behandelings-perseel, geoond-droog by 68 ˚C, geweeg, gemaal en geanaliseer vir N, S, P, K, Ca, Mg, Na, Cu, Fe, Mn en Zn. Die oesopbrengsdata van die koring vir 26 jaar was voorsien deur die LNR-Kleingraan Instituut om bykomend te gebruik saam die gronddata.

Die metodes van strooi-wegdoening en bewerking het varierende gevolge gehad op grond organiese materiaalindikatore. Strooi wat nie gebrand is nie het totale N en S laat toeneem, maar organiese C laat afneem in vergelyking met die brand van strooi. Geen-bewerking het organiese C laat toeneem slegs in die 0-50 mm gronddiepte in vergelyking met deklaag- en konvensionele bewerking. Geen-bewerking en deklaagbewerking lei tot hoër totale N tot op ‘n gronddiepte van 450 mm relatief tot konvensionele bewerking. Konvensionele bewerking, en tot ‘n mate deklaagbewerking, het egter totale S laat toeneem meer as geen-bewerking in die boonste 250 mm gronddiepte. Geen-bewerking en tot ‘n mate deklaagbewerking het versuring onderdruk in die boonste 100 mm en onderste 350-450 mm gronddiepte. Meganiese onkruidbeheer het ook die grond pH laat toeneem wanneer dit vergelyk word met chemiese onkruidbeheer. Geen-bewerking gekombineer met chemiese onkruidbeheer of brand van strooi, het versuring onderdruk in die oppervlak grond, terwyl meganiese onkruidbeheer gekombineer met geen-bewerking of konvensionele bewerking ‘n vertraging van versuring in die ondergrond tot gevolg het. Die konsentrasies van P, K, Mg, Mn en Zn was hoër in die gebrande behandelings as in die ongebrande behandelings. Die teenoorgestelde kon waargeneem word met Ca, Na en Cu. In teenstelling het konvensionele bewerking, en tot ‘n mindere mate geen-bewerking daar toe bygedra dat Cu geakkumuleer het in die boonste 100 mm gronddiepte wanneer geen-bewerking gedien het as ‘n verwysing. Chemiese onkruidbeheer het P, K, Mg, Na en KUK verhoog, maar het gelei tot ‘n laer Ca, Cu, Fe, Mn en Zn inhoud wanneer vergelyk word met meganiese onkruidbeheer.

Die toegepaste bestuurspraktyke was ook getoets op voedingstofopname en oesopbrengs. Alhoewel nie altyd betekenisvol nie, het die brand van reste voedingstofopname laat toeneem, maar het gelei tot ‘n laer koring oesopbrengs wanneer dit vergelyk word met ongebrande reste. Ten spyte van die voordelige effekte van geen-bewerking en deklaagbewerking op die vrugbaarheidsstatus van hierdie Avalon grond, is hoër voedingstofopname en oesopbrengste onder konvensionele bewerking waargeneem. Meganiese onkruidbeheer het ook die opname van meeste van die voedingstowwe verhoog relatief tot chemiese onkruidbeheer. Konvensionele bewerking gekombineer met ongebrande reste of chemiese onkruidbeheer het voedingstofopname en koring oesopbrenste verhoog. Alhoewel, ongeag van die toegepaste behandelings, was die voedingstof konsentrasies in die hawerreste onder die optimum vlakke, en plante het moontlik reeds akute voedingstoftekorte gehad.

Sleutelwoorde: Grondvrugbaarheid, koring oesopbrengste, oesrestebestuur, voedingstofopname

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DEDICATION

This work is dedicated to my mother Mrs ‘Makhathatso Loke and my father the late Mr Khanyane Loke. I never believed I will go this far, but your love and support kept me on my toes. Thank you for believing in me.

CHAPTER 1

Motivation and objectives

1.1 Motivation

Intensive crop production, triggered by the increasing world population, has resulted in insurmountable problems of soil nutrient outflows. This is attributed to a breakdown of cheap and safe soil fertility maintenance and improvement strategies, like land fallowing, mixed crop-livestock farming and agro-forestry practices (Mokwunye *et al*., 1997). Consequently, the nutrient supplying capacity of soil for optimum plant growth and yield declined. Research ascribes soil fertility decline and hence reduced crop production to inadequate inputs relative to losses, mainly through harvesting, volatilization, leaching and erosion (Mokwunye *et al*., 1997). In order to stabilize soil fertility and ensure food security, it is therefore necessary to replace the lost nutrients.

The existing approaches to soil fertility replenishment include applications of chemical fertilizers and organic materials. However, lack of knowledge by farmers in the use of commercial inputs leads to improper soil management practices. Additionally, the use of chemical fertilizers is not as widely practised or even possible in developing countries, due to escalating prices of chemical inputs, low income and hence limited credit to most farmers (Bakht *et al*., 2009). As a result, these chemical fertilizers are rarely applied at the recommended rates or appropriate time, with a suitable method of placement. Indeed the use of commercial inputs has resulted in increased yield and labour effeciency, but their perpetual use has led to a serious organic matter decline, erosion and even eutrophication of rivers and lakes (Kotzé, 2004). It is against this backdrop that efforts have to be made to identify alternative agricultural practices that will optimize productivity and profitability, while promoting and maintaining soil productive capacity and environmental quality (Havlin *et al*., 1999).

Emerging evidence shows that conservation practices and continuous applications of organic sources are the only feasible methods for improving low fertility soils, and crop production at both national and household level, while maintaining a good environment. This calls for recycling and management of crop residues. Crop residues, including plant roots, are remnants of the previous crop left in the field after harvesting and threshing (Mandal *et al*., 2004; Yadvinder-Singh *et al*., 2005; Rengel, 2007). At times these crop residues were regarded as farm wastes, but recently it was realized that they can be a primary source of soil organic matter and plant nutrients (Mandal *et al*., 2004; Bakht *et al*., 2009). However, the quantities of nutrients released in the soil system upon residue decomposition, and the content of organic matter, depend on the quality of crop residues and their management, as well as on the complex processes governing residue decomposition (Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007). This prompted Mandal *et al*. (2004) to conclude that every residue management option has its benefits and limitations.

Management options available to farmers include (1) residue retention on the soil surface, (2) residue incorporation into the soil, and/or (3) residue burning or removal after harvesting (Mandal *et al*., 2004; Bhupinderpal-Singh & Rengel, 2007). Tillage methods applicable to different residue management practices range from conservation tillage (no-tillage, minimum or reduced tillage and stubble mulch tillage) to conventional tillage systems (mouldboard plough and disc plough). A combined use of residue retention and conservation tillage systems increases soil organic matter and nutrients in the surface soil, buffers against raindrop impact, suppresses evaporation (salinization) and erosion, and thereby improves water conservation (Lal, 2005; 2009). However, this management option provides microclimatic conditions that might be deleterious to crop yields, especially in humid climates (Lal, 2009). In addition, residue mulch encourages weed, disease and pest infestations and nutrient immobilization by soil microorganisms, as well as soil surface stratification of immobile nutrients. Expensive herbicides and implements used in this systems also counterbalance the benefits of conservation practices.

Incorporation of crop residues by tillage offers a conducive soil environment for seedling establishment, microbial activity and diversity, and hence nutrient transformations (Yadvinder-Singh *et al*., 2005). Higher nutrient uptake by plants and hence grain yield can therefore be expected under this management option (Martin-Rueda *et al*., 2007; Bakht *et al*., 2009). Conversely, tillage increases the risk of soil erosion and compaction, breaks up organic materials and exposes protected organic matter to microbial decomposers, resulting in great losses of organic matter and essential nutrients (Bhupinderpal-Singh & Rengel, 2007) .

Irrespective of the benefits of recycling crop residues, farmers in most developing countries remove crop residues for use as fodder and/or bedding for animals, building material or fuel, resulting in great nutrient exports from agro-ecosystems (Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007; Bakht *et al*., 2009). Sometimes crop residues are disposed of by burning in an attempt to ease tillage and seeding operations, to control weeds, pathogens and diseases, and to reduce impediment to the newly growing crops (Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007). Despite the fact that burned crop residues release nutrients in an available form and are a natural liming material (Rengel, 2007), residue burning can lead to: (1) air pollution, and hence global warming, due to the release of greenhouse gases (CO_2, N_2O and CH_4), (2) a considerable loss of essential nutrients and a negative long-term impact on soil organic matter and nutrient holding capacity and (3) deterioration of soil structure due to reduced binding agents (Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007; Limousin & Tesseir, 2007; Bijay-Singh *et al*., 2008). Therefore farmers who continuously dispose of crop residues after harvesting, need proper conservation programs which aim at demonstrating on how recycled crop residues can improve soil fertility and ultimately crop productivity (Bakht *et al*., 2009).

The most dominant forms of soil fertility deterioration on tilled soil in the Free State Province are erosion, acidification and organic matter degradation (Hensley *et al*., 2006).Therefore, management practices that ensure large amounts of crop residues to be returned to the soil can potentially address these problems. However, since improvements on soil fertility indicators may become apparent after a certain period of time (several decades), long-term studies are required to examine sustainability of these management strategies (Bhupinderpal-Singh & Rengel, 2007). The same authors again appealed that for full recognition of the benefits of crop residues on soil fertility, such research initiatives should focus not only on N, but also on other plant nutrients such as P, S and micronutrients, for which there is limited information. Yadvinder-Singh *et al*. (2005) added that data on the chemical composition of crop residues is needed for better prediction of the nutrient quantities released in the soil upon residue decomposition.

Studies regarding the influence of different residue management practices on some soil fertility indicators have been conducted since 1979, in a long-term wheat trial at the ARC-Small Grain Institute near Bethlehem in the Eastern Free State on an Avalon soil. Winter wheat (*Triticum aestivum* L. cv. Betta) is grown annually on the same plots with no intervening summer crop. A fallow is maintained during the five-month period between harvest and seeding, when most of the annual rainfall is expected, to accumulate precipitation. Management practices applied in this trial include methods of straw disposal, tillage and weed control. Soil samples are collected after every 10 years and analysed for various soil fertility indicators in order to examine the long-term effects of these management practices.

The tested management practices, particularly conservation practices, were said to show expected beneficial effects on soil fertility. However, higher nutrient and organic matter stratification as well as lower acidity in the surface soil as a result of conservation systems did not affect wheat grain yield (Wiltshire & Du Preez, 1993; Du Preez *et al*., 2001; Kotzé, 2004). Thus, conservation tillage systems resulted in lower grain yield when compared to conventional tillage. Nevertheless, about 31% of N and 38% of organic C were lost in the first 10 years from the cultivated area compared to the native pasture (Wiltshire & Du Preez, 1993). Despite that, in 1999 contrasting results were established with respect to the effect of straw disposal on soil organic matter, where higher organic C and lower total N were recorded under burned rather than unburned treatments (Kotzé, 2004). The 20 year results showed that nutrient and organic matter stratification still continues. Therefore, it was found necessary to further study these management practices after 30 years with the assumption that conservation practices (no-tillage, stubble mulch and unburned wheat straw) and chemical weeding will improve soil fertility and eventually nutrient uptake and grain yield. This study validates, to a large extent, the results obtained in 1989 and 1999.

1.2 Objectives

The objectives with this study were therefore to:

- Evaluate the effects of different wheat residue management practices after 30 years on some soil fertility indicators such as organic matter (organic C, total N and total S), soil acidity (pH), macronutrients (P, K, Ca, Mg and Na) and micronutrients (Cu, Fe, Mn and Zn).

- Compare the 30 year results of soil fertility indicators with the 20 year and 10 year results where possible.

- Establish whether nutrient uptake (N, P, K, Ca, Mg, S, Na, Cu, Fe, Mn and Zn) by plants (mid-shooting stage) was influenced by the nutrient stratification resulting from 30 years of different residue management practices.

- Determine whether wheat grain yield over the 30 years was affected by different residue management practices.

CHAPTER 2

Materials and methods

2.1 Experimental site and soil

The trial is located at the ARC-Small Grain Institute (28^{o}13'S and 28^{o}18'E; altitude 1680 m) near Bethlehem in the Eastern Free State. The effects of wheat residue management on soil fertility indicators were examined in this trial since 1979. The trial has been running for 30 years and the measurements were made every 10 years after the commencement of the trial. The 30 year measurements are reported in this study. As can be seen in Table 2.1 the mean annual rainfall is 743 mm and the mean annual class-A pan evaporation is 1815 mm, resulting in a mean annual aridity index of 0.41. Most of the rain (82%) falls from October to March, with mean daily temperatures ranging from 7.1 ^{o}C in July to 20.3 ^{o}C in January.

According to the Land Type Survey Staff (2001), the trial is found in the land type Ca6n that occupies 420 000 ha. This land type is defined as a plinthic catena which has in upland positions margalitic and/or duplex soils derived from Beaufort mudstone, shale, sandstone and grit, with dolerite sills in places.

The trial is laid out on a Soetmelk series (MacVicar *et al*., 1977) or Mafikeng family (Soil Classification Working Group, 1991) of an Avalon soil form which occupies about 17% of the land type, and occurs on a terrain unit 3 with a 2-3% north facing slope. In accord to the USDA system, the soil would fall under the great group Plinthustalfs (Soil Survey Staff, 1987). This Plinthosol (FAO, 1998) consists of three diagnostic horizons: an orthic Ap (0-300 mm), yellow brown apedal B1 (300-650 mm) and soft plinthic B2 (>650 mm), containing 18, 23, and 36% clay, respectively. The parent material comprises an aeolian or colluvial deposit on shale that increases with depth from 750 to 900 mm.

The historical background of the site before 1979 is not known, except that the soil was cultivated for at least 20 years before the commencement of the trial. Nevertheless, soil sampling was made in the headlands with perennial grass outside the trial, and such samples were analyzed (Table 2.2) for some soil fertility indicators to give an idea of the fertility status of the soil before the trial.

Table 2.1 Long-term climate data as retrieve from weather station 19833 at the ARC-Small Grain Institute near Bethlehem (ARC-ISCW, 2011)

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rain (mm)	120.7	104.4	86.6	45.1	19.0	11.3	7.0	24.8	29.7	83.7	107.6	103.1	742.9
E_0 (mm)	205.4	160.5	159.8	120.4	104.1	81.6	93.9	128.1	167.8	186.1	195.3	211.9	1814.9
AI	0.59	0.65	0.54	0.37	0.18	0.14	0.07	0.19	0.18	0.45	0.55	0.49	0.41
Tmax (°C)	26.8	26.2	24.7	22.1	19.3	16.3	16.5	19.2	22.6	23.7	24.8	26.3	22.4
Tmin (°C)	13.7	13.4	11.5	7.2	2.1	-1.7	-2.2	0.7	4.9	8.6	10.7	12.6	6.8
Tm (°C)	20.3	19.8	18.1	14.7	10.7	7.3	7.1	10.0	13.7	16.1	17.8	19.4	14.6

E_0 = Class A pan evaporation

AI = Aridity index which is the ratio of rainfall to class-A pan evaporation

Tmax = Mean daily maximum temperature

Tmin = Mean daily minimum temperature

Tm = Mean daily temperature, *viz.* (Tmax + Tmin)/2

Table 2.2 Mean values of soil fertility indicators in the headlands with perennial grass outside the trial

Depth (mm)	C (%)	N (%)	S (%)	C:N Ratio	C:S ratio	N:S ratio	pH (H_2O)	P (mg kg^{-1})	K (mg kg^{-1})	Ca (mg kg^{-1})	Mg (mg kg^{-1})	Na (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	Mn (mg kg^{-1})	Zn (mg kg^{-1})	CEC (cmol$_c$ kg^{-1})
0-50	1.54	0.13	0.02	11.85	77.00	6.50	5.7	12.0	276	1034	167	39	1.9	237	60	4.3	7.96
50-100	1.23	0.11	0.02	11.18	61.50	5.50	5.7	6.7	221	1039	154	63	2.0	218	42	3.2	7.36
100-150	0.81	0.07	0.02	11.57	40.50	3.50	5.9	5.0	195	1028	139	72	1.7	187	27	2.0	6.63
150-250	0.72	0.06	0.02	12.00	36.00	3.00	6.0	5.1	170	1136	144	86	1.5	104	27	1.4	6.45
250-350	0.69	0.06	0.03	11.50	23.00	2.00	6.0	3.8	140	1087	136	82	1.5	47	25	0.7	6.63
350-450	0.68	0.06	0.04	11.33	17.00	1.50	6.1	2.2	101	1082	151	84	1.4	30	16	0.3	6.62

2.2 Experimental layout and treatments

A randomized complete block design with three blocks (I, II and III) was used to lay out the experiment across a north-facing slope, with I being the highest and III being the lowest. Each block comprises 36 field treatments: two methods of straw disposal (burned and unburned) × three methods of tillage (ploughing, stubble mulch and no-tillage) × two methods of weed control (mechanical and chemical) × three levels of nitrogen fertilization (20, 30, and 40 kg N ha^{-1} until 2003, thereafter 20, 40 and 60 kg N ha^{-1} were used). Only the 40 kg N ha^{-1} plots were sampled. The size of each plot is 6 × 30 m with 10 m borders.

These plots are cropped annually with winter wheat (*Triticum aestivum* L.) without any rotation or replacement with a summer crop. A fallow period of five months is maintained in this trial to restore soil water between harvesting and seeding, during which most of the rainfall events are expected. In 1990, 2004 and 2010, oat was however, used as a substitute crop, as a way to reduce soil-borne diseases (Take-all) that occurred in some treatments. In 1992 no yield was realised due to drought.

Immediately after harvesting in December, wheat straw is burned or left unburned. Just after burning, a two-way offset disc is used to incorporate wheat straw ashes to 150 mm depth in cultivated treatments. The ploughed treatments are done by mouldboard plough to 250 mm soil depth in February or March when the soil is sufficiently moist and easy to work with. Stubble mulch is not disked, instead it is cut at 100-150 mm using a V-blade or rod weeder (replaced since 2003 by light tiller) and then ripped with a 50 mm width chisel plough at 300 mm spacing to the same depth as mouldboard ploughing; the no-tilled treatments are not ploughed.

During the five-month fallow period (between harvesting and planting) weeds are controlled either by mechanical cultivator (rod-weeder or V-blade depending on soil water level until 2003, since then a light tiller was used) or by spraying herbicides. Initially, Roundup was the common herbicide used in this trial. Later the non-selective herbicides glyphosate and Paraquat were used alternatively to prevent herbicide resistance developing. All the treatment plots were slightly disturbed with a combined seeder-fertilizer drill used for sowing *Triticum aestivum* L. cv Betta and 3:2:0 (25) + 0.75% Zn fertilizer application. The mixed fertilizer material was applied at a rate that results in N, P, K and Zn applications of 20, 13, 0 and 1 kg ha^{-1}, respectively. A thoroughly mixed limestone ammonium nitrate (28% N) with the fertilizer mixture was applied to supplement the deficit for N levels two (10 kg N ha^{-1}) and three (20 kg N ha^{-1}).

However, since 2003, a different planter (DBS No-tillage Planter) was used as it made it unnecessary to pre-mix fertilizer by hand. Application rates of the planter are computer-controlled and mix fertilisers from separate N and P sources automatically. The planter was set to accurately apply 20, 40 and 60 kg N ha^{-1} and a constant application of 12.5 kg P ha^{-1}. This change had the implication that the fertilizer sources used changed from a 3:2:0 (25) mixture to only LAN (28) and single Superphosphate (10%). The use of these different fertiliser sources could effect the application of S. A newer cultivar (Elands) was introduced in 2005 to replace Betta which has become obsolete.

2.3 Soil sampling, preparation and analysis

Composite soil samples were collected at the headlands outside the trial with a 70 mm diameter auger. Subsamples were collected at two sites 50 m apart, 100 m from the highest, and at two sites 50 m apart, 100 m from the lowest corner of the trial and mixed thoroughly. Three auger cores (70 mm diameter) were taken from the centre-line of each treatment plot and mixed thoroughly. Soil samples from both outside and within the trial were taken at different layers: 0-50, 50-100, 100-150, 150-250, 250-350 and 350-450 mm. Soil sampling was done before planting in June 2010. The samples were dried at room temperature and sieved through a 2 mm sieve and then stored for analysis.

Chemical analyses were done in triplicate according to standard methods (The Non-Affiliated Soil Analysis Work Committee, 1990). The analyses that were carried out to determine selected soil fertility indicators are organic C (Walkley-Black method), total N (Kjeldahl method) and total S (Leco combustion), pH (1:2.5 soil to water suspension), exchangeable acidity (1 mol dm^{-3} KCl), extractable P (1 mol dm^{-3} $NaHCO_3$ at pH 8.5), exchangeable K, Ca, Mg, Na and CEC (1 mol dm^{-3} NH_4OAc at pH 7), extractable Cu, Fe, Mn, and Zn (DTPA-method).

2.4 Plant sampling and analysis

At mid-shooting stage, plants were sampled in each treatment plot, just above ground level in an area of one square meter during the 2010 growing season. Oat was used as a substitute crop in this particular year. The sampled plants were rinsed thrice with distilled water to remove soil dust, then oven-dried at 68 ºC for four days, weighed, milled and analysed for C, N and S (Leco combustion) as well as P, K, Ca, Mg, Na, Cu, Fe, Mn, and Zn (dry ashing with nitric acid). Nutrient uptake was then determined using nutrient content and plant biomass values.

2.5 Grain yield data

The grain yield data of wheat for the 26 years were supplied by the ARC-Small Grain Institute for use as a supplement to the soil data. During 1980, 1989, 1990, 2004 and 2010 seasons no grain data were recorded due to oat, while in 1992 no grain yield data were recorded due to drought. Unfortunately, no data on quantities of crop residues remaining on the soil surface after harvesting or planting were documented.

2.6 Statistical analysis

Analysis of variance was computed for every soil layer using measurement means of the stated soil fertility indicators. All analyses of variance were computed at a 95% confidence level using NCSS software package of Hintze (1997). This software was also used to compare treatment means with Tukey's (T) procedure at a 95% confidence level.

CHAPTER 3

Effects of wheat residue management on soil organic matter

3.1 Introduction

Soil organic matter is a mixture of organic substances that reside in the soil. It includes plant and animal remains that are in various stages of decomposition, a wide range of soil organisms, as well as dark-coloured humus consisting of humic and non-humic substances (Du Preez *et al*., 2011a). Some of these organic materials are fragile and therefore decompose faster than the more stable organic components. Such stable organic materials contribute positively to the build-up of soil humus, which in turn has a major effect on most soil properties that play a vital role on soil quality and ultimately on soil fertility.

Organic matter influences soil quality and fertility through its inherent physical, chemical and biological properties. Organic matter acts like a sponge in the soil, and through this action enhances air and water movement, water holding capacity, water infiltration and thus reduces runoff and erosion (Lal, 2009). The binding ability of organic matter is of utmost importance in the formation of highly stable soil aggregates, and thereby reduces surface crusting and compaction of the soil, while simultaneously promoting root growth and development. In addition, organic matter acts as a reservoir for a wide range of nutrients that are released slowly into the soil system upon decomposition and a natural habitat for soil organisms. The elements C, N and S are bound in organic matter, and can be seen as indices for soil organic matter (Kotzé & Du Preez, 2007). Apart from its chelating capacity and being a potential source of energy for soil biota, organic matter provides a considerable buffer capacity to the soil, due to its high ion exchange capacity (Kotzé & Du Preez, 2007).

All soils contain organic matter, but the content may vary depending on soil type, soil forming factors and specifically, management practices (Lal, 2005; Du Preez *et al*., 2011a). Although it might be difficult to screen short-term changes in organic matter as a result of land use, labile pools would respond more quickly than more recalcitrant pools, which are often associated with finer soil particles (Bhupinderpal-Singh & Rengel, 2007; Chivenge *et al*., 2007). However, irrespective of soil type, Mills and Fey (2003) indicated that soils subjected to intensive cultivation usually have lower organic matter content than undisturbed or virgin soils. This rests on the theory that tillage aerates the soil and induces rapid biological oxidation of organic matter (Chivenge *et al*., 2007; Kotzé & Du Preez, 2007), resulting in potential loss of C, N and S.

Soils in the arid and semi-arid areas are vulnerable to organic matter loss, especially when conventional tillage is practiced regularly (Mills & Fey, 2003; Kotzé & Du Preez, 2007). More than 30% of organic C losses are reported in every two decades of conventional tillage (Kotzé & Du Preez, 2007). The other possible contributory factors could be the warmer and drier climates in combination with crop residue removal for other domestic purposes. Despite the effect of environmental conditions and land use, South African soils are inherently low in organic C, ranging from less than 0.5% to just more than 2%, and only 4% of these soils are characterized by the latter proportion (Du Preez *et al*., 2011a). Nonetheless, Chen *et al*. (2009) proposed two ways in which soil organic matter can be maintained or improved in cropped landscapes: (1) increasing organic matter inputs and (2) decreasing soil organic matter loss and decomposition. These two mechanisms can be achieved by adopting and implementing proper crop residue management practices, coupled with conservation tillage systems.

Conservation practices, particularly no-tillage and crop residue retention, can improve soil organic C, N (Kotzé & Du Preez, 2007; Limousin &Tessier, 2007; Martin-Rueda *et al*., 2007; Thomas *et al*., 2007; López-Fando & Pardo, 2009; Van Den Bossche *et al*., 2009, Dalal *et al*., 2011) and S (Yadvinder-Singh *et al*., 2005) in the surface soil. This is due to the accumulation of crop residues near the soil surface and a minimal or lack of soil disturbance, resulting in slow residue decomposition. Lemke *et al*. (2010) and Dalal *et al*. (2011) on the other hand believe that no-tillage, without N fertilizer in particular, cannot improve organic matter. Although continuous application of N fertilizers induces soil acidification, which may lead to a great loss of carbonates (Lemke *et al*., 2010), fertilization enhances plant biomass production, and thus organic matter inputs (Lemke *et al*., 2010; Dalal *et al*., 2011).

Nitrogen fertilization is mostly done to reduce microbial immobilization of N, which on the other hand conserves substantial quantities of N by temporarily reducing its availability, and thus its leaching potential (Bhupinderpal-Singh & Rengel, 2007). Immobilization of N in the surface-managed residues can transform soil N into slowly available forms, which may subsequently act like a slow-release fertilizer (Yadvinder-Singh *et al*., 2005). This enhances the N supplying capacity of soils as well as N use efficiency (Yadvinder-Singh *et al*., 2005; Van Den Bossche *et al*., 2009). Subsequent crop growth can ultimately benefit due to N accumulation near the root zone (Yadvinder-Singh *et al*., 2005). In general, residue retention or supplement, and to a large extent the C:N and C:S ratios of added crop residues, play a key role in determining the rate of residue decomposition and organic matter fluxes.

Despite the overwhelming importance of S in growth and physiological functioning of plants, this nutrient has received relatively inadequate attention for many years because of plentiful supply from fertilizer inputs and atmospheric deposition (Scherer, 2001; Itanna, 2005; Eriksen, 2009). This situation changed only two to three decades ago (Eriksen, 2009). Now S deficiency has become a threat to crop production due to the increasing use of fertilizers devoid of S, controlled industrial SO_2 emissions, the use of high-producing cultivars, intensive agricultural practices and reduced use of S-containing pesticides (Scherer, 2001). Yadvinder-Singh *et al*. (2005) added that the decreasing use of organic manures, disposal (burning or removal) of crop residues and SO_4^{2-} leaching are also the major precursors to S deficiency in agricultural soils.

Sulfur in its mineral form is mobile and susceptible to leaching (Havlin *et al*., 1999; Scherer, 2001, Itanna, 2005; Yadvinder-Singh *et al*., 2005). Residue incorporation into the soil can reduce losses of S by leaching (Yadvinder-Singh *et al*., 2005), and maintain S fertility of soils since crop residues contain appreciable quantities of this nutrient (Itanna, 2005). Nevertheless, incorporation of crop residues by tillage may have short-term beneficial effects on soil S, because this leads to accelerated S mineralization (Houx III *et al*., 2011). In general, a decline in soil organic matter due to intensive cultivation would rapidly offset S reserves in soils (Itanna, 2005; Du Preez *et al*., 2011b).

The incorporation of crop residues by tillage, promotes residue decomposition and potential loss of organic matter through increased microbial activity and oxidative processes. Evidence from field experiments shows that residue management practices that involve intensive tillage (ploughing and mechanical weeding) deprive soils of organic matter (Kotzé & Du Preez, 2007). Shafi *et al*. (2007) and Bakht *et al*. (2009) also highlighted that incorporation of crop residues by tillage increases mineral N. Residue incorporation and continuous application of N fertilizers lead to the accumulation of mineral N (NO_3^-) in the soil profile. The amount required to meet crop demand is then often exceeded, thereby aggravating its potential to leaching (Al-Kaisi & Licht 2004; Vogeler *et al.*, 2009). Alternatively, surface retention of crop residues in no-tillage techniques may influence leaching and denitrification losses of N following increased water infiltration and suppressed evaporation rates (Yadvinder-Singh *et al*., 2005).

Despite the beneficial effects offered by no-tillage and residue retention, several reports showed that substantial accumulation of crop residues on the soil surface also hinder planting operations, seedling establishment and provides ideal conditions for pest and disease harbouring as well as weed infestations (Kumar & Goh, 2002; Mandal *et al*., 2004; Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007). Therefore farmers may opt to burn or remove crop residues after harvesting. Burning or removal of crop residues represents a major process responsible for soil organic matter degradation (Chan & Heenan, 2005). Straw burning destroys the residue layer at the soil surface and reduces the amount of organic materials expected to recharge pools of soil organic matter.

Mandal *et al*. (2004) estimated that stubble burning produces 13 ton ha^{-1} of CO_2, which pollutes the atmosphere and deprives soils of organic C. Heard *et al*. (2006) also reported that irrespective of straw type, more than 90% of C and N as well as 75% of S were lost in Manitoba Western Canada due to burning. According to Sharma and Mishra (2001), incomplete straw burning resulted in 100% loss of N while a certain amount (25%) of S might be recovered in ashes and partially burned residues. Compared to no-burning, Malhi and Kutcher (2007) indicated that straw burning reduced total organic C and N by 10%. However, Kotzé and Du Preez (2007) obtained contrasting results in this regard. They observed a slight increase in organic C and decrease in total N as a result of stubble burning.

The direction (accumulation or depletion) of organic C change during burning is determined by the quantity of crop residues burned and the degree of burning (Yadvinder-Singh *et al*., 2005). Apparently, farmers should consider burning crop residues after autumn break, when ambient temperatures are low, and humid conditions occur, because under such conditions complete straw burning is not accomplished (Chan & Heenan, 2005). Bhupinderpal-Singh and Rengel (2007) after reviewing a number of research works also stated that partially burned straw leaves recalcitrant pools of C behind that are less preferred by microorganisms as their source of energy; therefore, such recalcitrant pools may be accumulated over time and still be detected during soil analysis.

Stubble burning may have short-term benefits on the N supply to the succeeding crop growth, but a long-term negative impact on overall N fertility and soil quality (Yadvinder-Singh *et al*., 2005). Residue burning directly and indirectly reduces microbial activity and diversity, hence microbial immobilization of N and S, resulting in short-term availability of these nutrients (Bhupinderpal-Singh & Rengel, 2007). Conversely, large quantities of N and S from aboveground plant biomass are lost during and after burning (Sharma & Mishra, 2001; Heard *et al*., 2006). Eventually only small amounts are returned to the soil as ash, which can still be washed away by wind and/or water if retained on the soil surface. Long-term burning of crop residues also depletes N bound in organic matter due to its low temperature of volatilization (200 ^{o}C) (Bhupinderpal-Singh & Rengel, 2007). Kumar and Goh (2002) concluded that straw burning cannot be recommended as an option to farmers due to its deleterious effects on soil N. Chan and Heenan (2005) also pointed out that even though the negative impact of straw burning on organic C is relatively small compared to that of tillage, stubble burning has a potential for continual loss of organic C.

The use of herbicides and other weed control methods in crop production also influence soil organic matter (Kotzé & Du Preez, 2007). Weeds that are usually left at the soil surface as mulch after slashing, add to soil organic matter. In some instances, weeds may be disposed of or buried during mechanical weeding. Disposal of these weeds reduces the quantity of organic materials that would otherwise be recycled to enhance soil organic matter. Their incorporation during cultivation subjects protected organic matter to rapid microbial decomposition and erosive forces, and eventually soluble components of organic matter become susceptible to runoff or leaching (Alkaisi & Licht, 2004). Although the use of chemical inputs such as herbicides has become a major environmental concern, organic matter losses under chemically weeded soils are very limited when compared to those subjected to mechanical weeding (Kotzé & Du Preez, 2007).

In general, the direction and magnitude of soil organic matter depend on the tillage regime, intensity of fire, quantity and quality of residues returned to the soil, as well as on some environmental and edaphic factors. Therefore with this chapter the aim is to evaluate the effects of different wheat residue management practices after 30 years on soil organic matter, and compare, where possible, the present results with those obtained in 1999 and 1989.

3.2 Results and discussion

3.2.1 Organic C

As illustrated in the summary of analyses of variance (Table 3.1), organic C as a measure of organic matter was notably influenced by tillage more than either straw disposal or weed control methods. Weeding combined with either tillage or straw disposal methods also had a significant influence on organic C.

Main effects

Although there were no significant differences in any of the soil layers, the burned plots had a slightly higher organic C content than unburned plots throughout the soil profile (Figure 3.1). These findings are similar to those shown for this trial after 20 years (Kotzé, 2004). Straw burning reduces microbial activity, and thus residue decomposition, resulting in an accumulation of relatively resistant pools of soil C (Bhupinderpal-Singh & Rengel, 2007). However, the opposite was reported by some researchers in other parts of the world (Malhi & Kutcher, 2007; Dalal *et al*., 2011). In most cases, this variation occurs due to differences in

Table 3.1 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on organic C at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A						
B	*			*		*
AB						
C		*				
AC	*	*	*	*	*	*
BC	*	*	*	*	*	*
ABC		*		*		

[a]A: straw disposal, B: tillage, C: weeding

fire intensity, sampling depth as well as climatic conditions (Yadvinder-Singh *et al*., 2005).

As displayed in Figure 3.1, different tillage systems influenced this index throughout the considered soil layers; however, the significant effect was observed in the 0-50, 150-250 and 350-450 mm depth intervals only. In the 0-50 mm soil layer, no-tillage increased organic C by 0.07% compared to both stubble mulch and ploughing. In the 150-250 mm and 350-450 mm soil layers respectively, the mean organic C contents were 0.57 and 0.51% in the mulched plots, 0.59 and 0.51% in the no-tilled plots and 0.67 and 0.61% in the ploughed plots. In fact, below 100 mm depth, higher organic C contents were recorded under ploughed plots compared to either no-tilled or stubble mulched plots. Calegari *et al*. (2008) found that organic C in the deeper soil layers under no-tillage is either equal to or lower than under conventional tillage. In this study organic C under the ploughed plots was similar throughout the six soil layers studied, suggesting a homogeneous distribution of this index by tillage implements.

Weed control methods had a lesser effect on organic C compared to tillage methods. In the 50-100 mm interval, organic C differed significantly between the weeding methods (Figure 3.1). Organic C content in this soil layer was 0.61% in the chemically-weeded and 0.66% in mechanically-weeded plots. Even below 100 mm soil depth, plots that were mechanically weeded had a slightly higher organic C content than plots that were chemically weeded. Compared to mechanical weeding, chemical weeding showed a minor increase in this index only in the upper soil layer (0-50 mm).

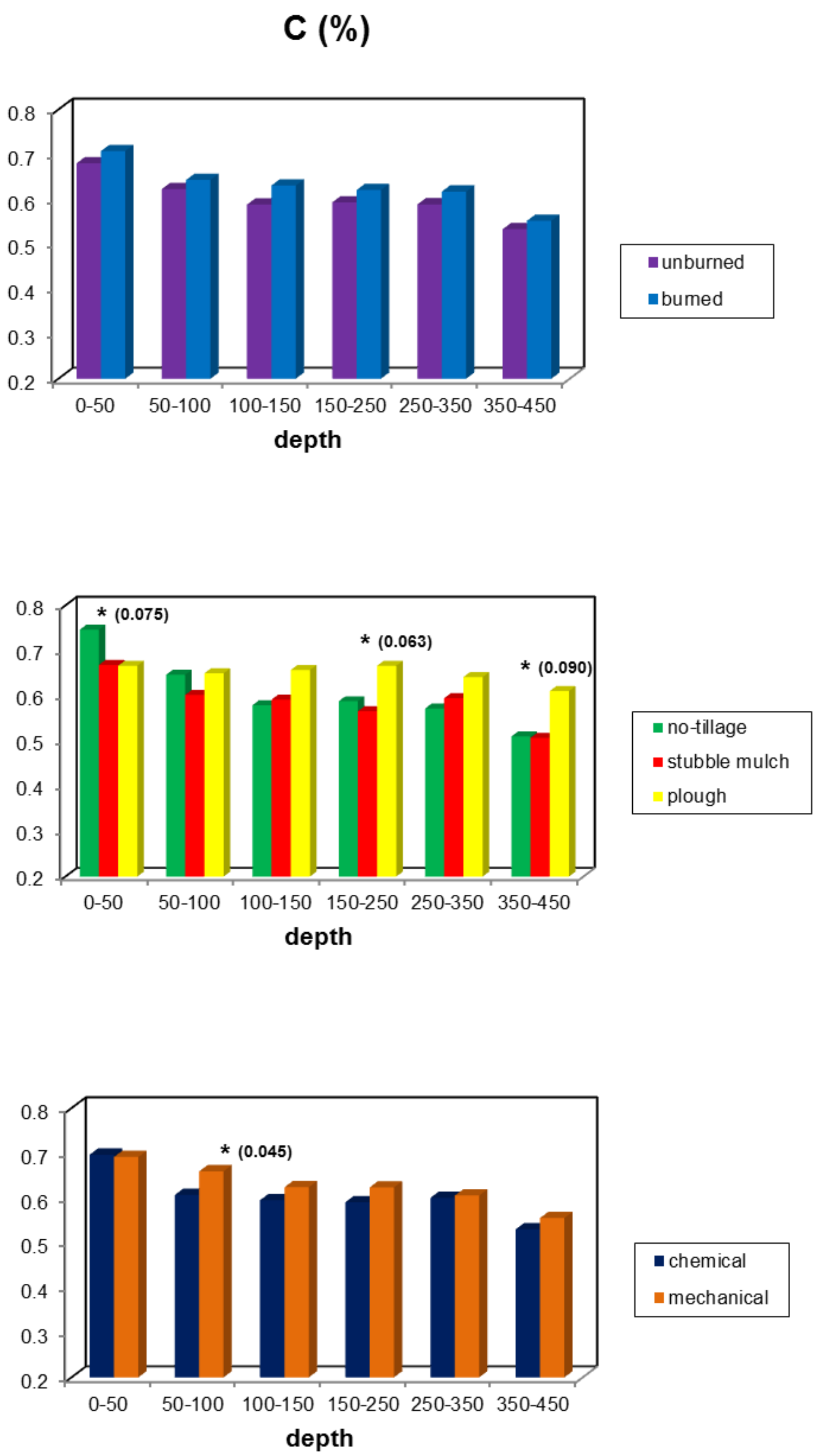

Figure 3.1 Effect of straw disposal, tillage and weed control methods on organic C. LSD_T-values are shown where applicable.

Interactions

The interactive effects of different treatments on organic C are summarized in Table 3.2. As indicated in the summary of analyses of variance (Table 3.1), the combination of either straw disposal or tillage with weeding caused a significant effect on organic C across all depth intervals. The chemically-weeded burned plots had a greater organic C content than mechanically-weeded burned plots, while mechanically-weeded unburned plots had a higher organic C content than the chemically-weeded unburned plots with the LSD_T values of 0.10, 0.08, 0.12, 0.08, 0.13 and 0.12% respectively to a soil depth of 450 mm. Except in the 150-250 mm layer, where both interactions, namely no-tillage combined with either chemical or mechanical weeding, had a similar amount of organic C, the chemically-weeded plots increased this index compared to mechanically-weeded plots when no-tilled or ploughed. When mulched, on the contrary, the amount of organic C was greater under mechanically-weeded plots than under the chemically-weeded plots in all the six layers. The LSD_T values in the tillage-weeding interaction were 0.13% in the 0-50 mm, 0.12% in the 50-100 mm, 0.16% in the 100-150 mm, 0.11% in the 150-250 mm, 0.18% in the 250-350 mm and 0.16% in the 350-450 mm soil depths. The interaction between tillage and straw disposal did not affect this index.

Table 3.2 Effect of the interactions between straw disposal, tillage and weed control methods on organic C (%)

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	0.77	0.65	0.62	0.61	0.75
	Burned	0.72	0.69	0.71	0.79	0.63
Weeding	Chemical	0.82	0.55	0.72		
	Mechanical	0.67	0.78	0.62		
50-100 mm layer						
Straw	Unburned	0.67	0.56	0.64	0.54	0.71
	Burned	0.62	0.64	0.66	0.68	0.61
Weeding	Chemical	0.67	0.49	0.66		
	Mechanical	0.62	0.72	0.64		
100-150 mm layer						
Straw	Unburned	0.57	0.56	0.63	0.51	0.66
	Burned	0.59	0.62	0.68	0.68	0.58
Weeding	Chemical	0.59	0.51	0.69		
	Mechanical	0.57	0.68	0.63		
150-250 mm layer						
Straw	Unburned	0.59	0.53	0.66	0.52	0.67
	Burned	0.58	0.61	0.67	0.66	0.58
Weeding	Chemical	0.59	0.46	0.72		
	Mechanical	0.59	0.67	0.61		
250-350 mm layer						
Straw	Unburned	0.57	0.56	0.63	0.52	0.66
	Burned	0.57	0.63	0.65	0.68	0.56
Weeding	Chemical	0.58	0.51	0.71		
	Mechanical	0.56	0.68	0.57		
350-450 mm layer						
Straw	Unburned	0.54	0.47	0.59	0.45	0.61
	Burned	0.48	0.54	0.63	0.61	0.50
Weeding	Chemical	0.54	0.39	0.67		
	Mechanical	0.48	0.63	0.55		

3.2.2 Total N

A summary of analyses of variance (Table 3.3) clearly shows that methods of straw disposal affected total N more than either tillage or weeding methods. The only significant interaction on total N was observed in the 150-250 mm soil layer between tillage and weeding methods.

Table 3.3 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on total N at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A	*	*	*			
B	*				*	
AB						
C			*	*		
AC						
BC				*		
ABC		*	*	*	*	

[a]A: straw disposal, B: tillage, C: weeding

Main effects

The total N of unburned plots was significantly higher than that of the burned plots, particularly in the upper three soil layers (Figure 3.2). The mean values for total N ranged from 0.058 to 0.065% in the 0-50 mm, 0.055 to 0.060% in the 50-100 mm and 0.055 to 0.057% in the 100-150 mm soil layers. In the other three deeper soil layers, there were no significant differences as a result of straw disposal; however, unburned straw continued to increase this index compared to the burned straw.

A further inspection of Figure 3.2 shows that different tillage systems had a significant influence on total N only in the 0-50 and 250-350 mm intervals. At 0-50 mm soil depth, the amount of total N was highest under no-tillage followed in a decreasing order by stubble mulch and then ploughing, *viz.* 0.066, 0.063 and 0.055%, respectively. In the 250-350 mm soil layer, the mulched plots had slightly higher total N than no-tilled plots, while both (mulched and no-tilled plots) had significantly higher total N than the ploughed plots. It is interesting however, to note that although the effect of tillage methods was significant only in the said layers, both no-tillage and stubble mulch increased total N throughout the soil profile compared to ploughing.

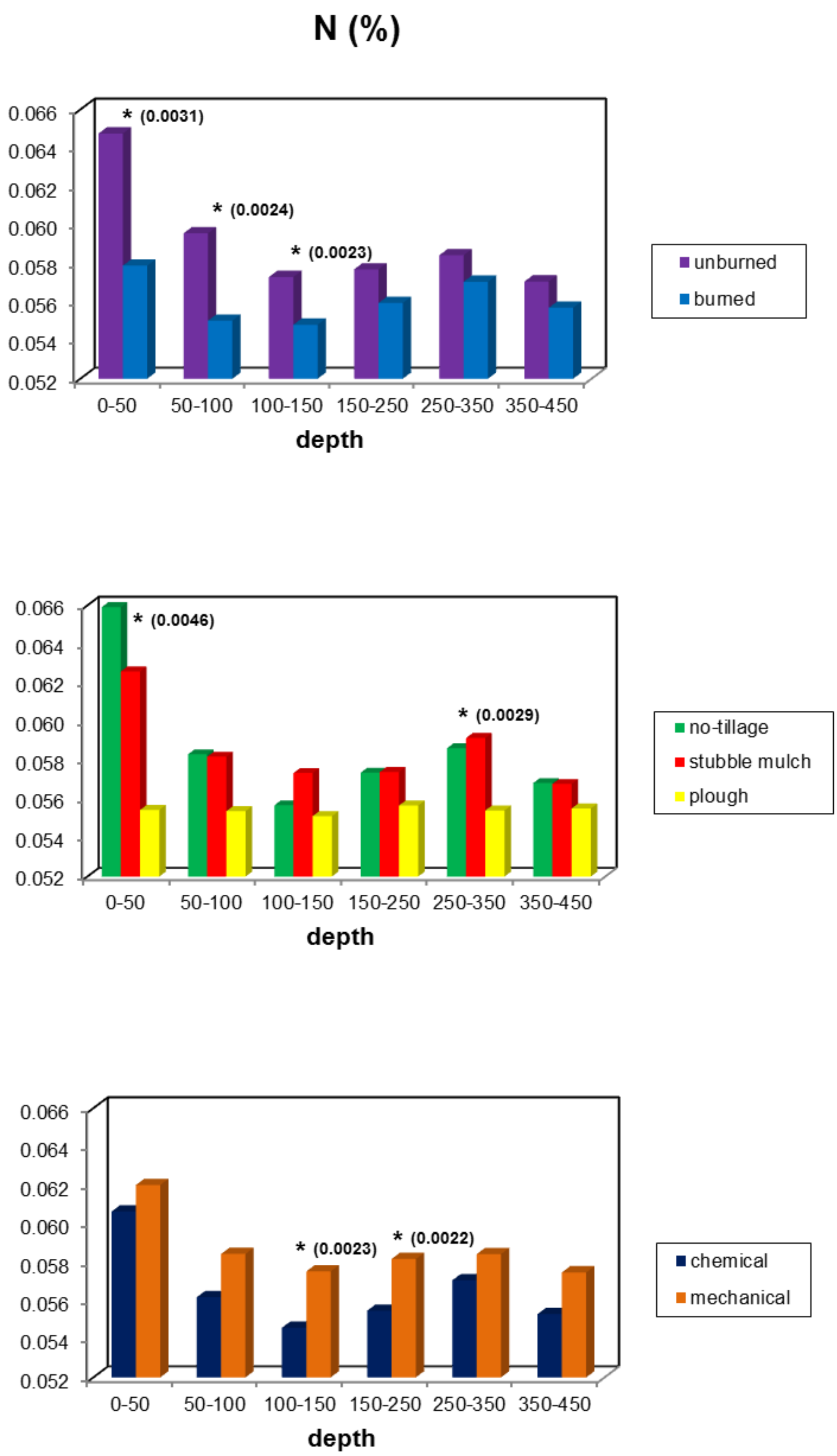

Figure 3.2 Effect of straw disposal, tillage and weed control methods on total N. LSD_T-values are shown where applicable

As with organic C, the total N of mechanically-weeded plots was higher than that of chemically-weeded plots throughout the soil profile (Figure 3.2). In the 100-150 and 150-250 mm intervals, the total N content differed significantly between the weeding methods. Thus, in both layers (100-150 and 150-250 mm) mechanically-weeded plots had on average 0.058% total N, while chemically-weeded plots had on average 0.055% total N.

Interactions

Data on the interactive effects of different treatments on total N are presented in Table 3.4. The significant interaction between tillage and weed control methods was noticed only in the 150-250 mm soil layer with an LSD_T of 0.006% (Table 3.3). In contrast to the mulched and ploughed treatments, mechanical weeding resulted in a significantly higher total N content in the no-tillage treatments when compared to chemical weeding. Despite insignificant difference, a similar pattern persisted in the other five depth intervals, where mechanically-weeded plots comprised slightly higher total N when not tilled and to some extent when mulched compared to the ploughed plots.

Methods of straw disposal combined with either tillage or weeding methods did not cause any significant effect in any of the studied soil layers. However, it can be indicated that irrespective of tillage or weeding method, unburned straw tended to increase total N compared to the burned straw except in the 250-350 and 350-450 mm soil layers.

Table 3.4 Effect of the interactions between straw disposal, tillage and weed control methods on total N (%)

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	0.069	0.066	0.059	0.064	0.066
	Burned	0.063	0.059	0.052	0.057	0.058
Weeding	Chemical	0.065	0.061	0.055		
	Mechanical	0.066	0.064	0.056		
50-100 mm layer						
Straw	Unburned	0.060	0.060	0.058	0.058	0.061
	Burned	0.056	0.056	0.053	0.054	0.056
Weeding	Chemical	0.057	0.056	0.055		
	Mechanical	0.060	0.060	0.056		
100-150 mm layer						
Straw	Unburned	0.056	0.058	0.058	0.056	0.059
	Burned	0.056	0.057	0.052	0.053	0.056
Weeding	Chemical	0.053	0.056	0.055		
	Mechanical	0.059	0.058	0.056		
150-250 mm layer						
Straw	Unburned	0.057	0.058	0.058	0.056	0.059
	Burned	0.057	0.057	0.053	0.055	0.057
Weeding	Chemical	0.054	0.057	0.056		
	Mechanical	0.061	0.058	0.056		
250-350 mm layer						
Straw	Unburned	0.059	0.059	0.058	0.057	0.060
	Burned	0.058	0.060	0.053	0.057	0.057
Weeding	Chemical	0.057	0.058	0.056		
	Mechanical	0.060	0.060	0.055		
350-450 mm layer						
Straw	Unburned	0.057	0.057	0.057	0.055	0.059
	Burned	0.056	0.057	0.054	0.056	0.056
Weeding	Chemical	0.055	0.055	0.055		
	Mechanical	0.059	0.058	0.056		

3.2.3 Total S

Despite the fact that crop demand for S is often similar or higher than that of P (Scherer, 2001; Eriksen, 2009), S has been neglected since the commencement of this trial. As presented in the summary of analyses of variance (Table 3.5), this index was affected significantly by weed control methods and to a larger degree more than either tillage or straw disposal. The combination between methods of straw disposal and tillage resulted in a significant effect on total S in the 50-100 mm soil layer.

Table 3.5 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on total S at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A		*	*			
B	*	*	*			
AB		*				
C		*	*	*	*	*
AC						
BC						
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Methods of straw disposal significantly affected total S at 50-100 and 100-150 mm soil depths, with S being higher in unburned plots than in the burned plots (Figure 3.3). The amount of total S ranged from 0.017 to 0.021% in the 50-100 mm and 0.018 to 0.024% in the 100-150 mm soil layers. There were no significant differences observed in the rest of the soil layers; however, plots that were burned had slightly higher total S only in the upper soil layer (0-50 mm) compared to unburned plots. This could be due to the fact that partially burned crop residues leave behind 25% of S in ashes (Sharma & Mishra, 2001; Heard *et al*., 2006).

Different tillage methods affected total S significantly up to a 150 mm soil depth (Figure 3.3). At 0-50 mm depth, the ploughed plots had the highest contents of total S (0.027%), followed by mulched plots (0.018%) and no-tilled plots (0.015%). In the 50-100 mm soil depth, the mulched and ploughed plots contained almost the same amount of this index, *viz* 0.022

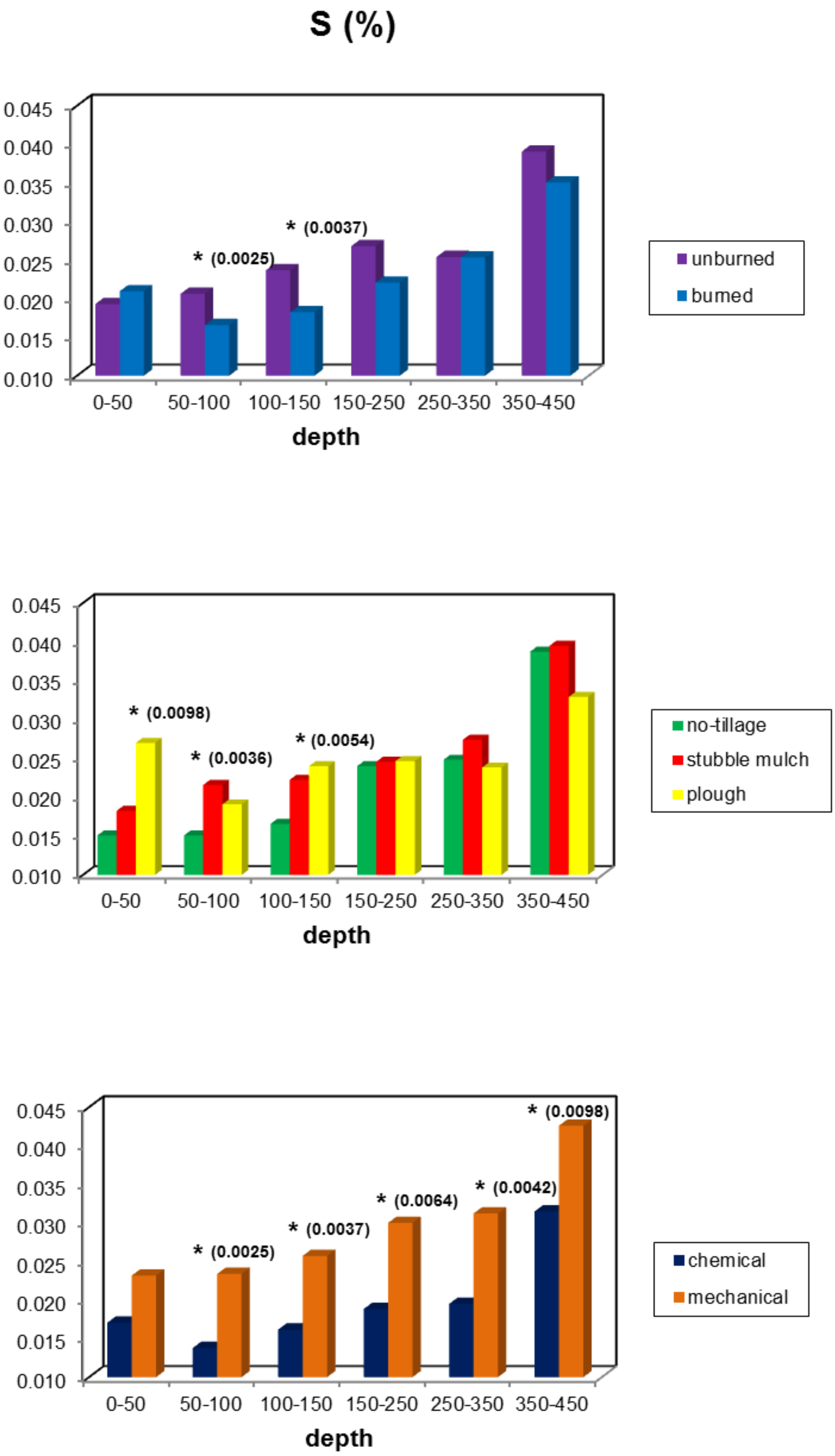

Figure 3.3 Effect of straw disposal, tillage and weed control methods on total S. LSD_T-values are shown where applicable

and 0.019%, respectively, but significantly more than no-tilled plots (0.015%). A similar trend was observed at 100-150 mm depth, although in this particular case ploughing resulted in a slightly high total S more than stubble mulch, while no-tillage reduced this index significantly compared to the other two tillage systems applied. Despite the negligible differences, both stubble mulch and no-tillage resulted in higher accumulation of S in the 250-350 and 350-450 mm soil depths compared to ploughing.

Weed control methods showed a robust effect on total S across all the soil layers, as can be seen in Figure 3.3. Mechanically weeded plots had higher total S compare to the chemically weeded plots in all the six depth intervals. However, the difference was statistically insignificant in the upper soil layer (0-50 mm). In contrast to both organic C and total N, total S increased with soil depth under all the applied treatments. A similar trend was also noticed in soil samples collected outside the trial (Table 2.2). This behaviour is indicative of high S mineralization followed by downward movement of the latter.

Interactions

Data on the effects of interactions between treatments on total S are given in Table 3.6. As can be witnessed in the summary of analyses of variance (Table 3.5), the only significant interaction was found between methods of straw disposal and tillage in the 50-100 mm soil depth with an LSD_T of 0.006%. At this soil depth, total S was significantly higher in the unburned plots that were ploughed (0.024%) compared to the burned plots that were ploughed (0.014%), while no significant differences were shown with no-tillage and stubble mulch.

No significant interactions could be found between methods of straw disposal and weeding. The combination of tillage and weeding methods also did not show any significant effect at any soil depth; however, some interesting trends were perceived in this regard. In all the six soil layers, mechanically weeded plots had slightly higher total S than the chemically weeded plots irrespective of the tillage method.

Table 3.6 Effect of the interactions between straw disposal, tillage and weed control methods on total S (%)

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	0.016	0.019	0.023	0.015	0.023
	Burned	0.015	0.017	0.031	0.019	0.023
Weeding	Chemical	0.011	0.015	0.026		
	Mechanical	0.020	0.022	0.028		
50-100 mm layer						
Straw	Unburned	0.016	0.023	0.024	0.015	0.026
	Burned	0.015	0.021	0.014	0.012	0.021
Weeding	Chemical	0.009	0.018	0.015		
	Mechanical	0.022	0.025	0.024		
100-150 mm layer						
Straw	Unburned	0.019	0.025	0.028	0.019	0.028
	Burned	0.014	0.020	0.020	0.013	0.023
Weeding	Chemical	0.013	0.017	0.019		
	Mechanical	0.020	0.028	0.029		
150-250 mm layer						
Straw	Unburned	0.028	0.026	0.027	0.021	0.032
	Burned	0.020	0.024	0.023	0.017	0.028
Weeding	Chemical	0.016	0.020	0.021		
	Mechanical	0.033	0.030	0.028		
250-350 mm layer						
Straw	Unburned	0.023	0.027	0.026	0.020	0.031
	Burned	0.026	0.028	0.022	0.019	0.032
Weeding	Chemical	0.018	0.021	0.020		
	Mechanical	0.032	0.034	0.028		
350-450 mm layer						
Straw	Unburned	0.049	0.035	0.033	0.033	0.045
	Burned	0.029	0.044	0.033	0.030	0.040
Weeding	Chemical	0.032	0.038	0.024		
	Mechanical	0.045	0.041	0.042		

3.2.4 C:N ratio

A summary of analyses of variance (Table 3.7) shows that the C:N ratio was significantly affected by methods of straw disposal and tillage. Weed control methods did not have any significant effect on the C:N ratio. The treatment combinations also showed a significant effect on C:N ratio.

Table 3.7 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on the C:N ratio at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A	*	*	*	*		
B	*	*	*	*	*	*
AB	*	*				
C						
AC	*	*	*	*	*	*
BC	*	*	*	*	*	*
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

In comparison to no-burning, straw burning increased the C:N ratio invariably to a 450 mm soil depth; however, significant differences between the two methods of straw disposal were perceived only in the upper four soil layers (Figure 3.4). This index varied from 10.5 to 12.3 in the 0-50 mm, 10.4 to 11.7 in the 50-100 mm, 10.3 to 11.6 in the 100-150 mm and 10.3 to 11.2 in the 150-250 mm soil layers. As indicated by Kotzé (2004), this response could be explained by higher organic C and lower total N measured in the burned plots as opposed to those that were not burned.

After 30 years since the commencement of this trial, ploughing resulted in a significantly higher C:N ratio in all depth intervals compared to the other two tillage systems applied (Figure 3.4). Apparently, high organic C and low total N in the ploughed plots, as can be seen in section 3.2.1 and 3.2.2, respectively, could be the source of a higher C:N ratio in the latter. However, López-Fando and Pardo (2009) attributed low C:N ratios in the deeper soil layers of no-tilled soil to increased organic matter humification and N mineralization.

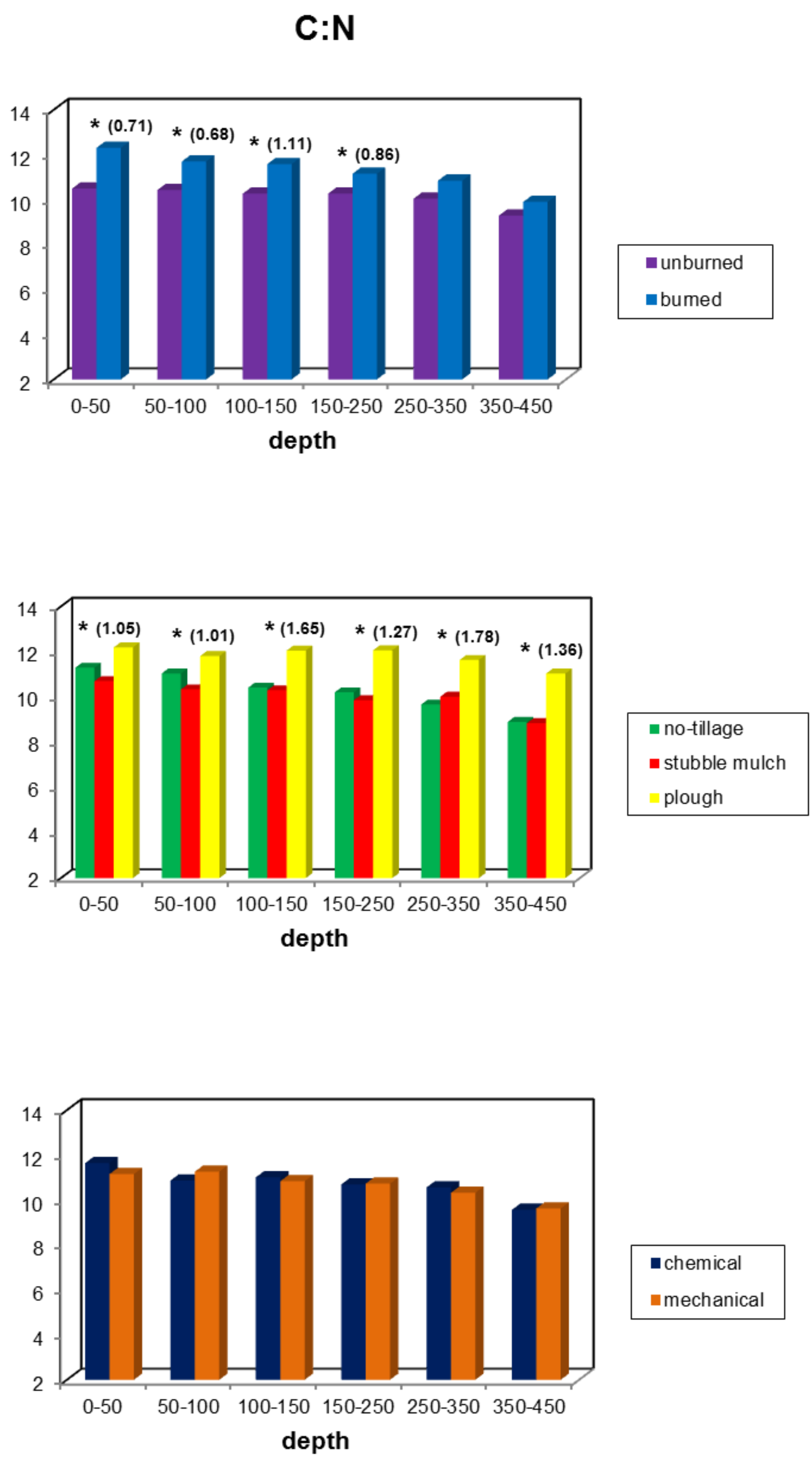

Figure 3.4 Effect of straw disposal, tillage and weed control methods on the C:N ratio. LSD_T-values are shown where applicable.

Weed control methods not only showed insignificant influence, but also inconsistency with regard to the C:N ratio (Figure 3.4). The chemically weeded treatments had a slightly higher C:N ratio in the 0-50, 100-150 and 250-350 mm depths, while mechanically-weeded plots showed a slight increase of this index only in the 50-100 and 250-350 mm soil layers. At 150-250 mm interval, the C:N ratio was 10.7 irrespective of the weeding method.

Interactions

Data on the interactions between different treatments on the C:N ratio are presented in Table 3.8. In contrast to the no-tilled treatments, straw burning increased the C:N ratio significantly in the ploughed and mulched plots when compared to no-burning. This response was observed in the 0-50 mm (LSD_T = 1.83) and 50-100 mm (LSD_T = 1.77) soil layers. Below 100 mm depth, the interaction of tillage and straw disposal showed insignificant and inconsistent trends with regard to the C:N ratio.

In all the six soil layers, the chemically-weeded burned plots had significantly higher C:N ratio than the chemically-weeded unburned plots, while mechanically-weeded unburned plots had a higher C:N ratio compared to mechanically-weeded burned plots (LSD_T = 1.33, 1.29, 2.10, 1.62, 2.27 and 1.73 respectively to a depth of 450 mm). The tillage-weeding interaction also influenced this index significantly across all the six soil layers with the LSD_T values of 1.83 in the 0-50 mm, 1.77 in the 50-100 mm, 2.89 in the 100-150 mm, 2.23 in the 150-250 mm, 3.11 in the 250-350 mm and 2.37 in the 350-450 mm soil layers. The combination of chemical weeding with either ploughing or no-tillage increased this index as opposed to the combination of mechanical weeding with either ploughing or no-tillage. In contrast, mechanically-weeded plots had a higher C:N ratio than the chemically-weeded plots when stubble mulch was applied.

Table 3.8 Effect of the interactions between straw disposal, tillage and weed control methods on the C:N ratio

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	11.14	9.70	10.63	9.50	11.48
	Burned	11.45	11.71	13.76	13.78	10.83
Weeding	Chemical	12.56	9.15	13.21		
	Mechanical	10.03	12.26	11.18		
50-100 mm layer						
Straw	Unburned	11.08	9.19	11.02	9.26	11.60
	Burned	11.01	11.49	12.60	12.48	10.92
Weeding	Chemical	11.81	8.66	12.13		
	Mechanical	10.27	12.02	11.50		
100-150 mm layer						
Straw	Unburned	10.28	9.68	10.85	9.20	11.33
	Burned	10.56	10.92	13.26	12.82	10.34
Weeding	Chemical	11.20	8.98	12.85		
	Mechanical	9.63	11.62	11.26		
150-250 mm layer						
Straw	Unburned	10.25	9.18	11.38	9.28	11.26
	Burned	10.16	10.55	12.76	12.11	10.20
Weeding	Chemical	10.85	8.18	13.05		
	Mechanical	9.56	11.54	11.08		
250-350 mm layer						
Straw	Unburned	9.65	9.50	10.97	9.14	10.95
	Burned	9.69	10.54	12.31	11.99	9.70
Weeding	Chemical	10.04	8.77	12.88		
	Mechanical	9.30	11.27	10.40		
350-450 mm layer						
Straw	Unburned	9.35	8.22	10.29	8.25	10.34
	Burned	8.44	9.47	11.78	10.88	8.91
Weeding	Chemical	9.66	6.92	12.11		
	Mechanical	8.13	10.77	9.97		

3.2.5 C:S ratio

As shown in the summary of analyses of variance (Table 3.9), the C:S ratio was affected by weed control methods and to a larger degree than either tillage or methods of straw disposal. The combination of straw disposal and weeding methods or tillage and weeding methods influenced C:S ratio significantly, though not in all the studied soil layers.

Table 3.9 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on the C:S ratio at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A			*			*
B	*	*				*
AB						
C	*	*	*		*	*
AC			*			*
BC	*	*				*
ABC	*					*

[a]A: straw disposal, B: tillage, C: weeding

Main effects

The C:S ratio of the burned plots was greater than that of unburned plots in all six soil layers measured (Figure 3.5). Nevertheless, the significant increase was observed only in the 100-150 mm soil layer. In this soil layer, C:S ratio varied from 26.15 to 42.99 for unburned and burned plots, respectively.

Tillage systems also exhibited a significant effect on the C:S ratio in the upper two soil layers as well as in the deepest soil layer (Figure 3.5). At the 0-50 mm interval, the no-tilled plots had the highest value for this index (71.56) followed in a decreasing order by mulched plots (39.61) and then the ploughed plots (29.43). At the 50-100 mm layer, the C:S ratio followed a similar pattern as in the upper layer; however, in this case the lowest value was recorded in the mulched plots. In this soil layer, this ratio was 56.87, 47.22 and 28.52 under no-tillage, ploughing and stubble mulch, respectively. In the lowermost soil layer (350-450 mm), the C:S ratio ranged from 13.40 in the mulched plots to 22.77 in the ploughed plots. An intermediate value for the C:S ratio (17.11) was recorded under no-tilled treatments. In the

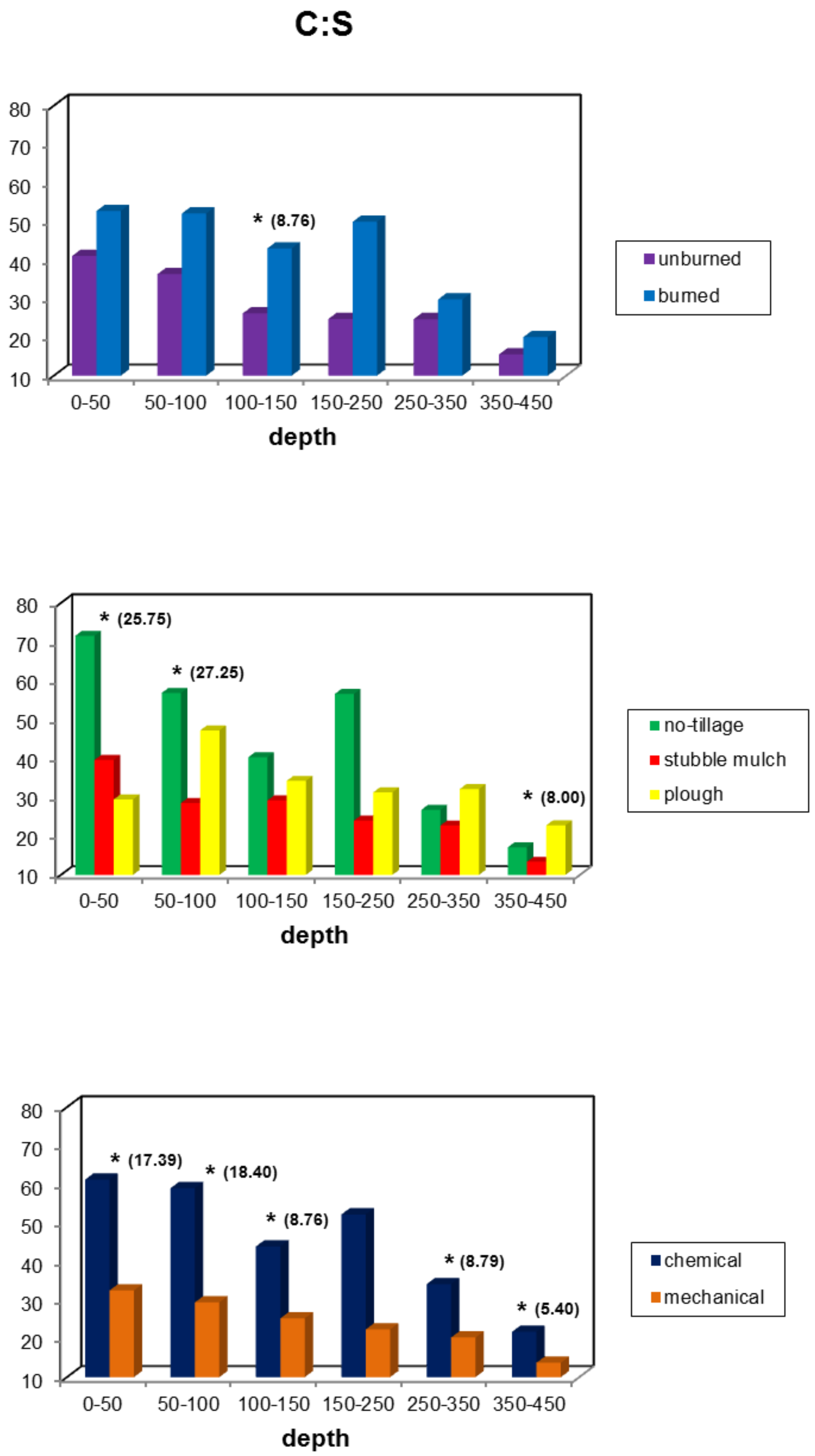

Figure 3.5 Effect of straw disposal, tillage and weed control methods on the C:S ratio. LSD_T-values are shown where applicable.

100-150 mm and 150-250 mm intervals, though the difference was not significant, no-tillage continued to increase this ratio compared to the other two tillage methods, while in the 250-350 mm soil layer, ploughing tended to increase the C:S ratio more than either no-tillage or stubble mulch.

Weeding methods significantly influenced the C:S ratio in the upper three and lower two soil layers (Figure 3.5). At these soil depths, the chemically-weeded plots had a greater C:S ratio compared to mechanically-weeded plots. Even though the difference was insignificant in the 150-250 mm layer, the C:S ratio was 22.38 in the plots that were mechanically weeded and 52.19 in the plots that were chemically weeded.

Interactions

Data on the interaction effects between treatments are presented in Table 3.10. As it can be seen in Table 3.9, significant interactions were found between straw disposal and weeding methods in the 100-150 mm and 350-450 mm soil layers as well as between tillage and weeding methods in the upper two soil layers and deepest soil layer. In the 100-150 mm and 350-450 mm soil layers with LSD_T values of 16.55 and 10.20 respectively, the chemically-weeded burned plots had higher C:S ratios than the chemically-weeded unburned plots, while mechanically-unburned plots contained higher C:S ratios than mechanically-weeded burned plots except in the 100-150 mm soil layer.

With regard to the combination between tillage and weeding, higher values for this ratio were observed in the chemically-weeded plots compared to mechanically-weeded plots, despite the tillage method, where significant differences were recorded at 0-50 mm, 50-100 mm and 350-450 mm depths (LSD_T = 45.08, 47.70 and 14.00 respectively) as indicated earlier in this section. In some cases however, particularly in the 50-100 mm and 350-450 mm intervals, mechanically-weeded mulched plots had a slightly higher C:S ratio than the chemically-weeded mulched plots. Across all the soil layers, there were no significant differences in the C:S ratio as a result of the interaction between tillage and methods of straw disposal.

Table 3.10 Effect of the interactions between straw disposal, tillage and weed control methods on the C:S ratio

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	59.08	34.27	29.72	46.99	35.06
	Burned	84.03	44.94	29.15	75.51	29.91
Weeding	Chemical	106.93	42.68	34.14		
	Mechanical	36.19	36.53	24.73		
50-100 mm layer						
Straw	Unburned	56.02	24.79	28.17	44.82	27.83
	Burned	57.71	32.24	66.27	73.18	30.97
Weeding	Chemical	85.00	28.22	63.78		
	Mechanical	28.74	28.81	30.65		
100-150 mm layer						
Straw	Unburned	31.41	23.40	23.66	27.88	24.43
	Burned	49.21	34.99	44.78	59.90	26.09
Weeding	Chemical	51.83	33.43	46.41		
	Mechanical	28.79	24.95	22.03		
150-250 mm layer						
Straw	Unburned	26.11	20.23	27.70	26.72	22.64
	Burned	87.09	27.76	34.83	77.66	22.13
Weeding	Chemical	92.89	25.04	38.64		
	Mechanical	20.31	22.95	23.89		
250-350 mm layer						
Straw	Unburned	25.69	21.49	26.77	27.15	22.15
	Burned	27.84	23.98	37.45	41.10	18.41
Weeding	Chemical	34.40	24.92	43.06		
	Mechanical	19.12	20.55	21.16		
350-450 mm layer						
Straw	Unburned	14.41	13.47	18.64	16.49	14.52
	Burned	19.82	13.32	26.90	27.07	12.95
Weeding	Chemical	22.48	11.10	31.76		
	Mechanical	11.74	15.69	13.78		

3.2.6 N:S ratio

A summary of analyses of variance is presented in Table 3.11. As can be seen in this table, the weeding methods had a strong influence on the N:S ratio compared to tillage or methods of straw disposal. Tillage combined with weeding methods affected the N:S ratio in the 0-50 mm soil depth.

Table 3.11 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on the N:S ratio at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A			*			
B	*	*				
AB						
C	*	*	*		*	*
AC						
BC	*					
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

The N:S ratio seemed to follow the same pattern as the C:N and C:S ratio with regard to the methods of straw disposal (Figure 3.6). The burned plots had a higher N:S ratio than unburned plots; however, the significant increase was found only in the 100-150 mm soil layer. In this soil layer, the N:S ratio ranged from 2.66 in the unburned plots to 3.65 in the burned plots.

The N:S ratio differed significantly in the 0-50 mm and 50-100 mm intervals as a result of tillage methods (Figure 3.6). The values of the N:S ratio were 2.52, 3.80 and 5.87 in the ploughed, mulched and no-tilled plots, respectively at the 0-50 mm soil depth and 2.80, 3.77 and 5.02 in the mulched, ploughed and no-tilled plots, respectively at the 50-100 mm soil depth. There were no significant difference in the deeper soil layers; however, no-tillage persistently increased this ratio slightly more than stubble mulch and ploughing in the 100-150 mm and 150-250 mm soil layers, whereas at 250-350 mm and 350-450 mm depths, the no-tilled and ploughed plots had a similar N:S ratio, but slightly higher than that of the

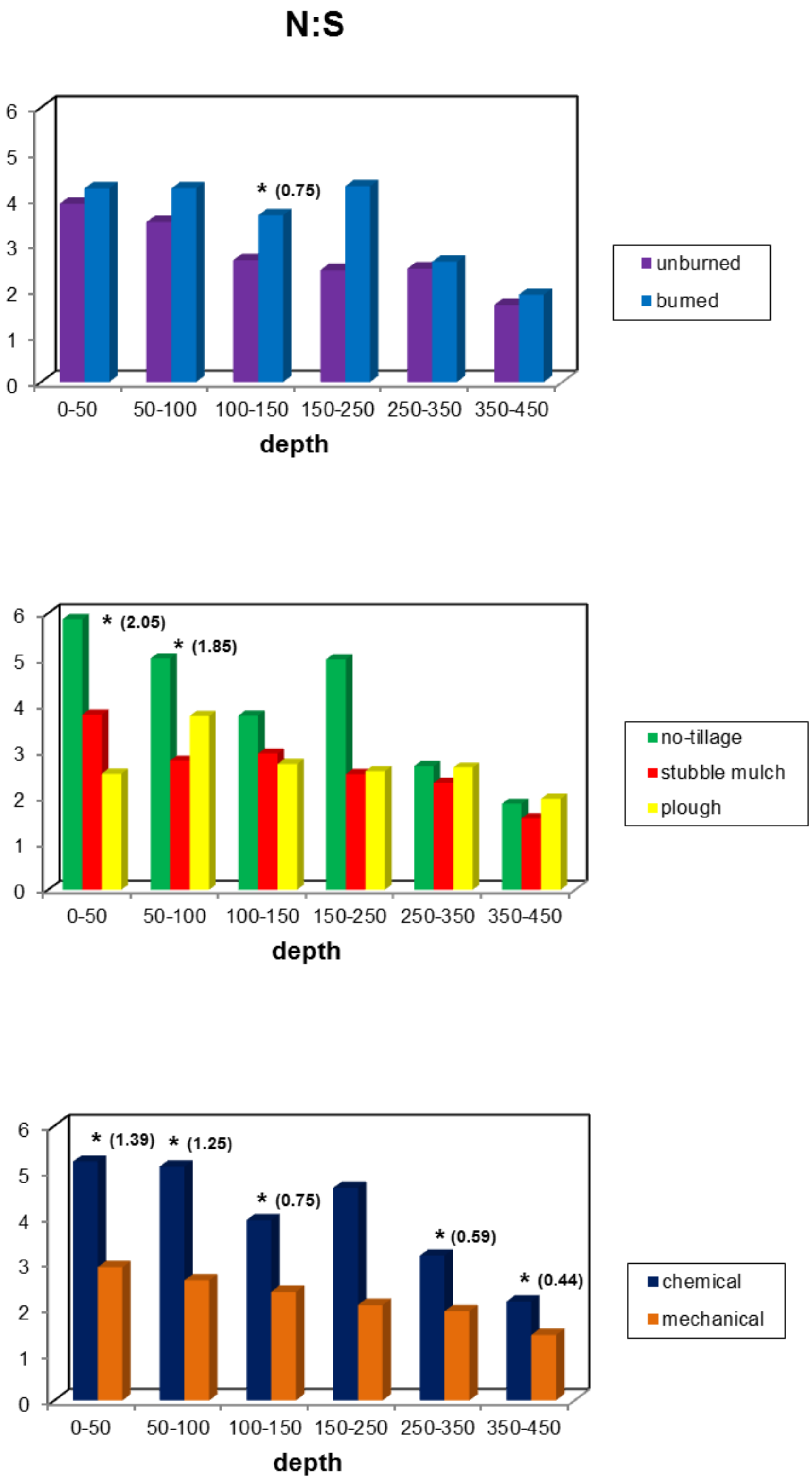

Figure 3.6 Effect of straw disposal, tillage and weed control methods on the N:S ratio. LSD_T-values are shown where applicable.

mulched plots.

The effect of weed control methods on the N:S ratio showed similar trends as the C:S ratio (Figure 3.6). The N:S ratio was significantly higher in the treatment plots that were chemically weeded than in the plots that were mechanically weeded, except in the 150-250 mm soil layer, where this difference was not significant. The N:S ratio of this soil layer (150-250 mm) was 2.08 in the mechanically weeded plots and 4.64 in the chemically weeded plots.

Interactions

Data on the interactive effects of different treatments on the N:S ratio are displayed in Table 3.12. The summary of analyses of variance (Table 3.11) shows that the only significant interaction was found in the 0-50 mm soil layer between tillage and weeding methods (LSD_T = 3.59). In this particular soil layer, the chemical weeding combined with either no-tillage or stubble mulch resulted in the higher N:S ratio when compared to mechanical weeding combined with either no-tillage or stubble mulch. The plots that were chemically weeded also had a slightly higher N:S ratio in all the other five soil layers than treatments that were mechanically weeded, regardless of tillage, with no-tilled plots showing the highest N:S ratio (from 50 to 350 mm depth).

There were no significant interactions observed between straw disposal and weeding or straw disposal and tillage; however, it can be remarked that the combination of straw burning and chemical weeding tended to increase this ratio to a 450 mm soil depth compared to the combination of no-burning and chemical weeding.

In general, results on organic C, total N and total S indicate that different treatments that have been applied for 30 years influenced organic matter content and distribution in this Avalon soil. The effects of these treatments however, varied from one index to the other. Organic C, total N and total S are indices of soil organic matter; nonetheless, they responded differently from one another on account of straw disposal methods. Therefore it is impossible to indicate clearly which method of straw disposal resulted in higher organic matter. In the introduction section however, few explanations are displayed regarding the response of individual indices to crop residue burning. Perhaps addition of N and S through fertilization can explain this response.

Similarly, tillage systems also showed inconsistent effects on organic matter as indicated by organic C, total N and total S. Organic C was significantly higher in the upper soil layer (0-50 mm) under no-tillage compared to stubble mulch and ploughing, but decreased rapidly with

Table 3.12 Effect of the interactions between straw disposal, tillage and weed control methods on the N:S ratio

		Tillage			**Weeding**	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	5.22	3.64	2.84	4.74	3.05
	Burned	6.53	3.96	2.20	5.69	2.77
Weeding	Chemical	8.25	4.61	2.80		
	Mechanical	3.50	2.99	2.24		
50-100 mm layer						
Straw	Unburned	5.14	2.75	2.60	4.59	2.40
	Burned	4.89	2.86	4.94	5.62	2.84
Weeding	Chemical	7.24	3.21	4.87		
	Mechanical	2.79	2.40	2.67		
100-150 mm layer						
Straw	Unburned	3.18	2.59	2.22	3.16	2.17
	Burned	4.38	3.32	3.24	4.71	2.58
Weeding	Chemical	4.56	3.77	3.49		
	Mechanical	3.00	2.14	1.97		
150-250 mm layer						
Straw	Unburned	2.61	2.31	2.42	2.89	2.00
	Burned	7.40	2.71	2.73	6.39	2.16
Weeding	Chemical	7.91	3.04	2.98		
	Mechanical	2.09	1.99	2.17		
250-350 mm layer						
Straw	Unburned	2.70	2.32	2.41	2.93	2.03
	Burned	2.67	2.32	2.90	3.39	1.86
Weeding	Chemical	3.39	2.81	3.28		
	Mechanical	1.98	1.83	2.03		
350-450 mm layer						
Straw	Unburned	1.54	1.70	1.80	1.97	1.40
	Burned	2.19	1.39	2.15	2.35	1.47
Weeding	Chemical	2.28	1.64	2.56		
	Mechanical	1.46	1.45	1.39		

increase in soil depth, while the total N contents increased throughout the six layers under conservation tillage systems compared to ploughing. As indicated in some studies (Kotzé & Du Preez, 2007; Martin-Rueda *et al*., 2007; Thomas *et al*., 2007; Calegari *et al*., 2008; López-Fando & Pardo, 2009), the influence of conservation tillage systems is more pronounced in the surface layers, resulting in a build-up of organic C and total N due to the surface placement of crop residues, lack of soil mixing, and low residue decomposition rate. Intensive and frequent tillage as opposed to conservation tillage disrupts soil aggregates and subjects protected organic matter to rapid microbial decomposition (Chen *et al*., 2009), resulting in potential loss of organic C, total N and total S. In this study, on the contrary, the ploughed plots had significantly higher total S in the upper three soil layers than the no-tilled and mulched plots.

The preceding results showed a rapid decline in organic C under no-tillage and stubble mulch as opposed to ploughing when the previous study (Kotzé, 2004) served as a reference. For example, in the 0-50 mm soil layer, the ploughed, mulched and no-tilled plots had respectively 0.60, 0.72 and 0.84% organic C after 20 years and 0.67, 0.67 and 0.75% organic C after 30 years, indicative that organic C under conservation tillage systems decreased as opposed to conventional ploughing. The increase in organic C in the ploughed plots was also observed in the deeper soil layers (below 100 mm). In this particular case, organic C was higher than that conceded under conservation tillage systems. Perhaps the recycled wheat residues after 20 years were inadequate to sustain organic C accumulation as compared to conventional ploughing. However, even if the amount of residues added were still enough, the pronounced response would be expected in the ploughed plots, which already had low organic C as shown by Kotzé (2004).

The amount of total N also dropped in the upper two soil layers (0-50 and 50-100 mm) as well as in the lower most soil layer (350-450 mm) after 30 years when compared to the amounts obtained after 20 years, despite a greater total N content under conservation tillage systems as opposed to mouldboard ploughing. Mineralization and uptake of N by wheat plants could be attributed to this phenomenon. However, in the lower soil layers (100-350 mm) the values of total N were higher than those presented by Kotzé (2004) after 20 years of this trial.

In contrast to the methods of straw disposal and tillage, weed control methods had a consistent influence on organic matter as indicated by organic C, total N and total S. Surprisingly, these indices of organic matter were generally higher in mechanically-weeded plots than in the chemically-weeded plots. These findings are not in agreement with the results reported in 1999 (Kotzé, 2004), and are unusual because any mechanical disturbance of the soil aerates the soil, resulting in rapid organic matter degradation. No explanation could be found regarding this response. Regardless of weeding method, both organic C and total N decreased after 30 years when compared to the 20 year results.

As can be seen in Table 3.13, management of wheat residues resulted in a decline of soil organic matter indices when compared to the perennial grassland outside the trial, except total S which remained the same under both grassland and inside the trial. This suggests that a change in land use can contribute significantly to a decline or improvement of soil organic matter (Du Preez *et al*., 2011b). The same authors indicated that conversion of natural grassland to cropland represent a basis for soil organic matter degradation. A decline in soil organic matter usually leads to low soil productive capacity following soil physical, chemical and biological degradation (Barnard & Du Preez, 2004; Van Den Bossche *et al.*, 2009). Recycling of crop residues as well as reduced tillage intensity can at least maintain or compensate for the lost soil organic matter in cropped soils (Schomberg *et al*., 1994). However, factors such as climate (rainfall and temperature), topography, parent material and time should be taken into consideration as they play an essential role in the build-up or loss of soil organic matter (Du Preez *et al*., 2011b).

Table 3.13 Weighted means of soil organic matter indices to 150 mm and 250 mm soil depths in the headlands with perennial grass outside the trial, and inside the trial cropped annually with wheat

Soil organic matter index	**0-150**		**0-250**	
	Headlands	**Trial**	**Headlands**	**Trial**
C (%)	1.19	0.65	1.00	0.63
N (%)	0.10	0.06	0.09	0.06
S (%)	0.02	0.02	0.02	0.02
C:N	11.90	10.83	11.11	10.05
C:S	59.50	32.50	50.00	31.50
N:S	5.00	3.00	4.50	3.00

3.3 Conclusion

The effects of different wheat residue management practices on organic matter were evaluated after 30 years of wheat cropping on an Avalon soil. Unfortunately, contrasting results on account of soil organic matter indices were observed when comparing the two methods of straw disposal as well as the three tillage systems. As a result it is impossible to show which method of straw disposal or tillage had a positive influence on organic matter of this Avalon soil. Application of N and S fertilizers may be responsible for contrasting results. However, the response of soil organic matter indices to the weeding methods indicated that mechanical weeding invariably increased soil organic matter when compared to chemical weeding.

There were significant interactions between different treatment combinations on organic matter indices. However, due to lack of consistency it becomes difficult to specifically single out the combination that seemed to be more effective than the others. Based on the results of this study it can be concluded that the combination of chemical weeding and straw burning, mechanical weeding and no-burning as well as no-tillage and chemical weeding increased organic C. No-tillage combined with mechanical weeding resulted in an accumulation of total N, while no-burning combined with either mouldboard ploughing or mechanical weeding enhanced total S.

CHAPTER 4

Effects of wheat residue management on soil acidity

4.1 Introduction

Soil acidification is a natural and/or human-induced process that occurs due to a resulting increase in the concentration of H ions in the soil solution. Among other factors, nutrient availability, plant growth, herbicide persistence and microbial activity and diversity depend on soil acidity (Kotzé & Du Preez, 2008). Since soil pH is a measure of H ion activity in the soil, it can be affected by various reactions occurring in the soil. Such reactions and factors that lead to pH change are accelerated by agricultural practices. Mineral hydrolysis, redox reactions, C, N and S cycling, application of NH_4-based fertilizers and lime, crop removal and/or leaching of NO_3 and exchangeable bases (Ca, Mg, K and Na), crop rotation and decomposition of organic materials are all sources of soil pH change. Therefore, in consideration of these factors, it would be unfair to solely attribute changes in soil pH to crop residue management, and to some extent, conflicting results between studies can be credited to these factors (Xu *et al*., 2006).

However, a renewed interest in crop residues as a source of organic matter and plant nutrients (Kotzé, 2004) has led to increased attention on the effect of different crop residue management practices on soil pH. Several incubation studies have investigated the potential of crop residues in ameliorating soil acidity (Xu & Coventry, 2003; Xu *et al*., 2006; Wang *et al*., 2010; Yuan *et al*., 2011), presumably in an attempt to alleviate resource-poor farmers from the economic burden of purchasing expensive liming materials. Xu *et al*. (2002); Xu and Coventry (2003) and Xu *et al*. (2006) found that recycling of crop residues can cause soil pH to increase, decrease or remain constant. The direction and magnitude of soil pH change are determined by soil properties and the chemical composition of added plant materials (Xu *et al*., 2002; Xu & Coventry, 2003; Xu *et al*., 2006; Yuan *et al*., 2011). Thus, high ash alkalinity of plant residues and mineralization of organic N increase soil pH, while nitrification of mineralized N and NH_4-based fertilizers and associated H production decrease soil pH (Xu *et al*., 2002; Xu & Coventry, 2003; Xu *et al*., 2006).

Soils under no-tillage tend to be more acidic in the surface layers than in the deeper layers as opposed to those under conventional tillage. This can be explained by high accumulation of plant materials, root density and fertilizer placement near the surface of no-tilled soils (Limousin & Tessier, 2007). Besides root exudation of organic acids and N fertilization (Limousin & Tessier, 2007), crop residues concentrated on or near the soil surface stimulate acidification of no-tilled soil through accumulation of CO_2, as well as organic and inorganic acids during their decomposition (Yadvinder-Singh *et al*., 2005). Dissociation of these decomposition products liberates H ions, resulting in a pH decline. Thomas *et al*. (2007) as well as López-Fando and Pardo (2009) confirmed this phenomenon after observing a significant negative correlation between organic matter and soil pH under no-tillage. As organic matter under no-tillage increased, mainly in the upper soil layers, soil pH declined. The same tendency was also noticed by Martin-Rueda *et al*. (2007).

Decomposition of organic matter accompanied by strong mineralization of organic N and associated consumption of protons can increase initial soil pH, which may drop with time due to subsequent nitrification. Typically, this occurs where crop residues with high N content (legumes) are returned to the soil (Xu *et al*., 2002; Wang *et al*., 2010). Improved hydraulic conductivity and reduced evaporation under no-tillage (Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007) can also trigger soil surface acidification through leaching of soluble salts and subsequent replacement of base-forming cations on the exchange complex by H and Al ions generated through organic matter decomposition and mineral disintegration, respectively (Kotzé, 2004). However, leaching of base-forming cations can still occur under conventional tillage due to increased drainage after cultivation. Cultivation mixes top-acid layers with alkaline-rich subsoil (or vice versa), and chances for surface acidification are reduced, unlike in no-tillage.

In contrast, Du Preez *et al*. (2001) and Kotzé and Du Preez (2008) observed a rise in pH of no-tilled plots compared to stubble mulched and ploughed plots almost throughout the soil profile. Although wheat straw has low ash alkalinity and N content, this can still lead to an increase in soil pH, particularly if the initial pH of the soil is lower than that of the wheat straw (Wang *et al*., 2010). Generally, there are at least four factors that contribute to soil pH increase following addition of plant residues: (1) decarboxylation of organic anions (malate, citrate and oxalate) upon residue decomposition, (2) ammonification of residue N, (3) association of some organic compounds with H and Al ions (through ligand bonding), and (4) high concentration of exchangeable base cations in crop residues (Xu & Coventry, 2003; Xu *et al*., 2006; Wang *et al*., 2010; Yuan *et al*., 2011). In addition, silica-rich crop residues also manifest all the benefits of mitigating soil acidity (Mandal *et al*., 2004).

According to Mandal *et al*. (2004), several studies showed a rise in soil pH regardless of whether crop residues are incorporated, retained or burned, suggesting that the method of residue management may have little or no effect on soil reaction. Yadvinder-Singh *et al*. (2005) on the other hand indicated that the effect of crop residues on soil pH may be insignificant, but management strategies may considerably influence soil pH. Nonetheless, long-term studies (over 10 years) revealed that straw burning increases soil pH as opposed to surface-managed residues (Du Preez *et al*., 2001; Xu *et al*., 2002; Kotzé & Du Preez 2008). The common practice of burning crop residues directly, adds plant residue ashes to the soil. Ashes derived from plant material contain substantial amounts of oxides, hydroxides and carbonates of alkali and alkaline earth metals that can correct soil acidity (Xu *et al*., 2002; Rengel, 2007). They can also ameliorate Al and Mn toxicities and P, Mo, Ca and Mg deficiencies, and therefore improve crop yields (Wang *et al*., 2010). Alternatively, straw burning may indirectly reduce soil acidity through a reduction in microbial activity (Bhupinderpal-Singh & Rengel, 2007), and hence processes and reactions that lead to pH decline (i.e. residue decomposition, nitrification and microbial respiration).

The significance of burning crop residues extends even in conservation practices where weed infestations seem to discourage farmers. However, burning may not particularly provide excellent results where cropped soils are infested by vegetative reproducing weeds. As a result, mechanical and chemical weed control methods are usually used as alternatives.

Mechanical weeding, which is known to accelerate organic matter decomposition and increase the leaching potential of NO_3^- and exchangeable base cations through better aeration and drainage, is likely to reduce soil pH when compared to chemical weeding (Du Preez *et al*., 2001; Kotzé & Du Preez, 2008). The leaching of NO_3^-, which is normally accompanied by positively charged ions (Ca, Mg, K and Na) (Kotze, 2004) leaves behind H ions to balance the charge, thereby increasing soil acidification. Conversely, the study on the effects of two commonly used herbicides on microflora indicated that atrazine alone caused a significant decline in soil pH as opposed to the combination of atrazine and metalachlor (Ayansina & Oso, 2006). The reason pertaining to this variation was not stipulated, but this could possibly be related to the composition of the herbicides.

On account of this discussion, it is explicitly clear that different residue management practices, amounts of residues returned to the soil, residue composition, plant species and soil properties such as initial pH, moisture content, drainage, buffer capacity and parent material play a pivotal role in altering the pH status of soils. Therefore the aim with this chapter is to evaluate the influence of different wheat residue management practices that have been applied consecutively for 30 years on soil acidity and to compare the current results with those reported in 1999 and 1989.

4.2 Results and discussion

The summary of analyses of variance (Table 4.1) indicates that soil pH as a measure of soil acidity was influenced significantly by tillage and to a lesser extent by weeding methods. Methods of straw disposal did not show any significant effect on soil pH. The treatment combinations had some significant effects on soil pH in the deeper soil layers (250-350 and 350-450 mm).

Table 4.1 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on soil pH at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A						
B	*	*		*		*
AB					*	
C						*
AC						*
BC					*	*
ABC				*	*	*

[a]A: straw disposal, B: tillage, C: weeding

Main effects

In all the six soil layers there were no significant differences in soil pH as a result of the methods of straw disposal (Figure 4.1). However, unburned plots had slightly higher pH values than the burned plots in the upper two soil layers only. Below 100 mm soil depth, straw burning resulted in higher pH values when compared to no-burning. Several researchers found that the burned crop residues release base cations in soluble forms that can move down the profile to mitigate soil acidification in the deeper soil layers as reviewed by Bhupinderpal and Rengel (2007). In 1989, all the sampled soil layers of the burned plots had higher pH than those of unburned plots (Du Preez *et al*., 2001). Kotzé and Du Preez (2008) found significantly higher pH in the surface soil layers (to 150 mm soil depth) of the burned plots compared to unburned plots.

Different tillage systems had a significant effect on soil pH except in the 100-150 and 250-350 mm soil intervals, wherein the ploughed plots showed slightly higher pH values than the no-tilled and mulched plots (Figure 4.1). Comparing the soil depths of 0-50 and 50-100 mm,

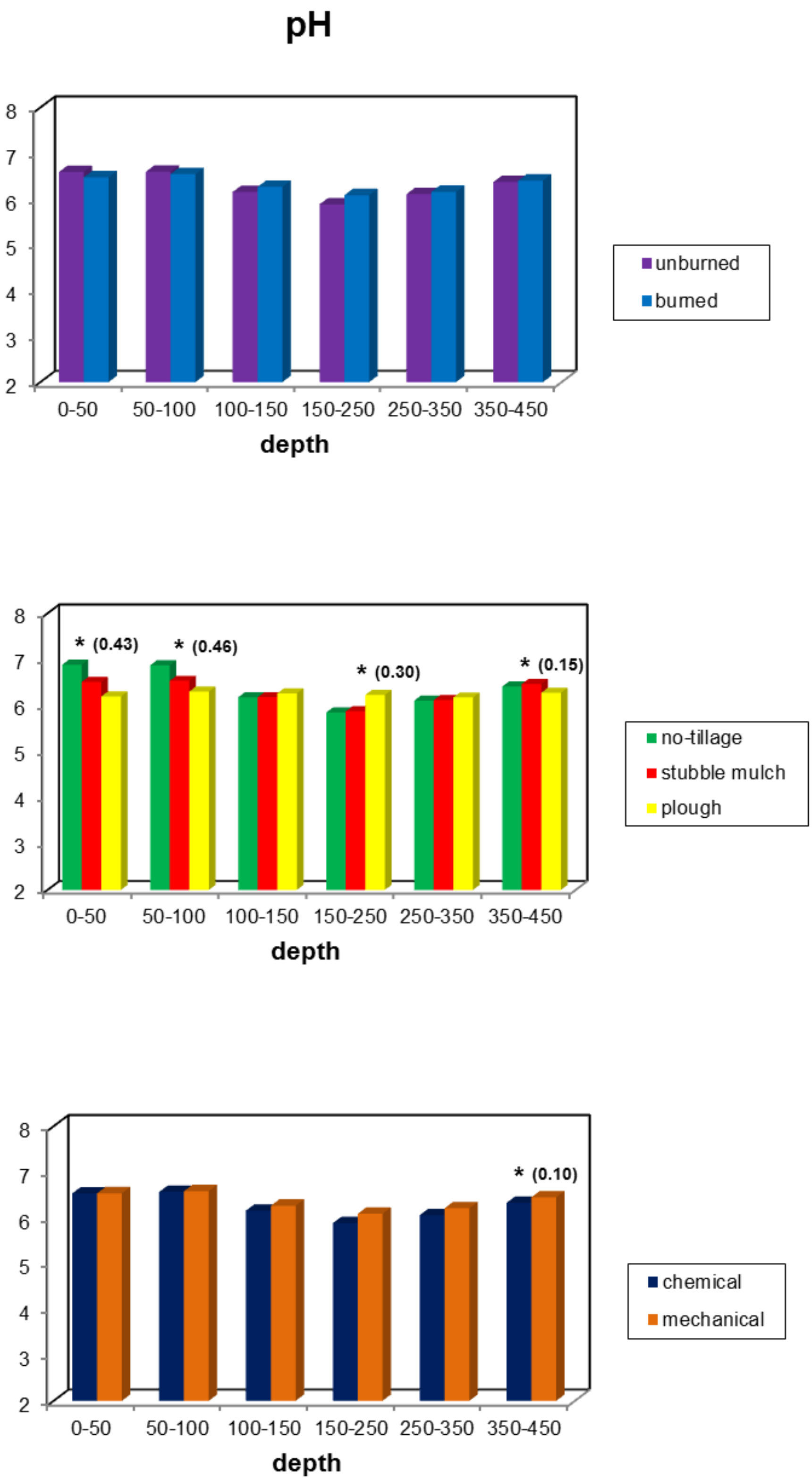

Figure 4.1 Effect of straw disposal, tillage and weed control methods on soil pH. LSD_T-values are shown where applicable.

the pH values varied respectively from 6.20 and 6.31 in the ploughed plots to 6.89 and 6.87 in no-tilled plots with the mulched plots being intermediate with pH values of 6.51 and 6.54. This trend however, changed below 100 mm soil depth. In the 150-250 mm soil layer, the highest pH value was recorded in the ploughed plots (6.23) followed in a decreasing order by stubble mulched plots (5.88) and then no-tilled plots (5.85), whereas in the 350-450 mm soil interval, the mulched plots (6.47) had the highest pH value followed by no-tilled plots (6.41) and then the ploughed plots (6.28). Du Preez *et al*. (2001) also measured the highest pH values in the no-tilled plots followed by the mulched and then the ploughed plots in all the considered soil layers. After 20 years since the commencement of this trial, Kotzé and Du Preez (2008) indicated that no-tillage continued to suppress soil acidification even as deep as 450 mm compared to stubble mulch and mouldboard ploughing.

As displayed in Figure 4.1, the weeding methods had a significant effect on soil pH only in the deepest soil layer, namely the 350-450 mm. The mean pH values in this soil layer ranged from 6.33 in the chemically-weeded plots to 6.45 in mechanically-weeded plots. There were no significant differences in the other five soil layers; however, mechanically-weeded plots had slightly higher pH values than the chemically-weeded plots throughout the soil profile. Du Preez *et al*. (2001), on the contrary, observed higher pH in the plots that were subject to chemical weeding as opposed to those that were exposed to mechanical weeding. Kotzé and Du Preez (2008) reported slightly lower pH in the upper three soil layers under mechanically-weeded plots rather than chemically-weeded plots. From the present results, it can be deduced that the initial pH of mechanically-weeded plots was lower than that of the returned wheat residues. Consequently, the added wheat residues managed to increase the pH of the plots that were mechanically weeded more than the chemically-weeded plots that already had a higher pH as indicated by Kotzé and Du Preez (2008).

Interactions

The interactive effects of different treatments on soil pH are presented in Table 4.2. As illustrated in the summary of analyses of variance (Table 4.1), significant interactions were perceived at 250-350 and 350-450 mm soil depths. In both layers, no-tillage combined with mechanical weeding had the highest pH values (6.33 and 6.64 respectively), while no-tilled plots that were chemically weeded had the lowest pH values (5.89 and 6.19 respectively) with LSD_T values of 0.43 and 0.23 respectively. In the 250-350 mm soil interval, the combination of tillage and straw disposal methods also affected soil pH significantly (LSD_T = 0.43) with the no-tilled plots that were burned showing the highest pH value (6.29) and the no-tilled plots that were not burned showing the lowest pH value (5.93). At 350-450 mm soil intervals again, significant interactions (LSD_T = 0.19) was recorded between weeding and

Table 4.2 Effect of the interactions between straw disposal, tillage and weed control methods on soil pH

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	6.75	6.73	6.30	6.67	6.51
	Burned	7.03	6.30	6.10	6.40	6.56
Weeding	Chemical	7.03	6.53	6.04		
	Mechanical	6.75	6.50	6.36		
50-100 mm layer						
Straw	Unburned	6.69	6.75	6.35	6.64	6.55
	Burned	7.05	6.33	6.26	6.48	6.61
Weeding	Chemical	6.97	6.54	6.18		
	Mechanical	6.77	6.54	6.43		
100-150 mm layer						
Straw	Unburned	5.96	6.28	6.22	6.14	6.17
	Burned	6.40	6.09	6.31	6.18	6.35
Weeding	Chemical	6.10	6.22	6.15		
	Mechanical	6.26	6.15	6.38		
150-250 mm layer						
Straw	Unburned	5.58	5.84	6.23	5.85	5.92
	Burned	6.11	5.91	6.23	5.92	6.25
Weeding	Chemical	5.66	5.92	6.08		
	Mechanical	6.04	5.84	6.39		
250-350 mm layer						
Straw	Unburned	5.93	6.15	6.25	6.10	6.12
	Burned	6.29	6.09	6.10	6.02	6.30
Weeding	Chemical	5.89	6.21	6.08		
	Mechanical	6.33	6.03	6.27		
350-450 mm layer						
Straw	Unburned	6.33	6.52	6.27	6.37	6.37
	Burned	6.50	6.42	6.29	6.28	6.52
Weeding	Chemical	6.19	6.55	6.24		
	Mechanical	6.64	6.39	6.32		

straw disposal methods with mean pH values ranging from 6.28 respectively in the chemically-weeded burned plots to 6.52 in mechanically-weeded burned plots.

Although the differences were insignificant in the other soil layers (to 250 mm), some interesting trends were noted. In the upper two soil layers (0-50 and 50-100 mm), no-tilled plots that were either burned or chemically weeded tended to have a higher pH than any other combination. A similar pattern persisted in the 100-150 mm soil interval where no-tilled plots that were subjected to burning had a higher pH than other treatment combinations. Irrespective of tillage or weeding method, straw burning increased soil pH more than no-burning at 150-250 and 250-350 mm soil depths with the no-tilled as well as mechanically-weeded plots showing higher pH values.

Du Preez *et al*. (2001) on the other hand indicated that the methods of straw disposal and tillage had a significant interaction only in the 0-50 mm soil interval. In this soil layer, the burned plots had a higher pH value than unburned plots, regardless of the applied tillage systems; however, the no-tilled plots showed the greatest effect followed by the mulched and then the ploughed plots. More or less the same observations were reported in 1999 (Kotzé & Du Preez, 2008). The significant interaction was then recorded in the upper two layers where the burned and no-tilled plots had the highest pH while the unburned and mulched plots had the lowest. In both studies there were no significant interaction between tillage and weeding or method of straw disposal and weeding.

In general, the methods of straw disposal and weeding had a lesser influence on soil pH than the tillage systems. The pH level in the 0-50 and 50-100 mm soil intervals was greater in no-tillage than in stubble mulch and greater in stubble mulch than in mouldboard ploughing, while in the 350-450 mm layer the mulched and no-tilled plots had higher pH values than the ploughed plots. The opposite was recorded in the other three soil layers (from 100 to 350 mm) where the ploughed plots exhibited higher pH values than the no-tilled and mulched plots.

These observations, to some extent, confirm the findings of the previous studies (Du Preez *et al*., 2001; Kotzé & Du Preez, 2008). However, Thomas *et al*. (2007) indicated that tillage did not affect soil pH in all the considered soil layers. Other researchers showed lower pH, especially in the surface layers, under conservation tillage systems rather than mouldboard ploughing due to surface application of N fertilizers and crop residues as well as lack of soil mixing (Limousin & Tessier, 2007; López-Fando & Pardo, 2009). Conversely, in this study all the sampled plots received the same amount of N fertilizer which was also banded to the same depth (Du Preez *et al*., 2001). Therefore the acidifying effect of N fertilizer in this study is hardly a reason why the ploughed plots had lower pH values than no-tilled or mulched plots, particularly in the upper two soil layers. Higher pH status in the upper soil layers of no-tilled and mulched soil can however, be ascribed to the four factors that contribute to high soil pH as mentioned earlier under the introduction section.

As was the case in 1999 (Kotzé, 2004), the no-tilled plots that were burned continued to show higher pH than the mulched and ploughed plots. This phenomenon can be attributed to the liming potential of burned residues (Xu *et al*., 2002; Rengel, 2007) and lack of soil disturbance, which limits an intimate interaction between ash and soil particles in no-tillage systems. Regardless of the field treatments applied, these pH increases are higher than the values established by Du Preez *et al*. (2001) and Kotzé (2004) as well as those observed from the soil samples taken outside the trial (Table 2.2). In general, this clearly highlights that management of wheat residue still proceeds to suppress acidification of this Avalon soil, and in spite of the variable effects of the applied treatments, the pH values observed in the present study are generally within the range at which most nutrients become available for plant uptake. Therefore application of commercial liming material is not necessary.

Numerous researchers argued that acidity reduces the productive capacity of soil and poses nutritional limitations in plants due to reduced availability of some essential nutrients, leaching and displacement of base forming cations as well as increased solubility of micronutrient cations, which may lead to their losses and/or toxicities to plants as reviewed by Barnard and Du Preez (2004). In their study, Barnard and Du Preez (2004) appealed that reduced tillage intensity serves as tool to enhance the general fertility of the soil including soil acidification. Therefore this study as well as the previous ones (Du Preez *et al*., 2001; Kotzé & Du Preez, 2008) showed that burning of wheat straw and conservation tillage practices can rehabilitate acidification, which has been shown to be the most prominent source of declining soil fertility in South Africa (Barnard & Du Preez, 2004).

4.3 Conclusion

Methods of straw disposal did not significantly affect the pH of this Avalon soil. However, unburned plots had a slightly higher pH only to a soil depth of 100 mm compared to the burned plots. In the 100 mm soil depth, no-tillage resulted in the highest pH values followed by mulch tillage and then mouldboard ploughing. Below 100 mm soil depth, tillage methods showed variable effects on soil pH. The weeding methods had a significant effect only in the 350-450 mm soil layer. Even so, mechanical weeding increased soil pH to 450 mm soil depth compared to chemical weeding. The combination of no-tillage with either chemical weeding or straw burning also seemed to retard acidification of this Avalon soil, especially in the upper two soil layers, while the combination of mechanical weeding with no-tillage or ploughing appeared to offset the subsoil acidification.

CHAPTER 5

Effects of wheat residue management on some macronutrients and CEC in soil

5.1 Introduction

Depending on their quantities required for plant nutrition, macronutrients can be classified as either primary (N, P and K) or secondary (Ca, Mg and S) macronutrients. In soils, these nutrients exist in various forms, but their exchangeable or readily-available pool is a good indicator of soil fertility. Nutrients in their exchangeable form are kept from leaching by CEC, which also signifies mineral fertility of the soil (Ben Moussa-Machraoui *et al*., 2010). Due to the fact that macronutrients are required and utilized in large amounts by crops, they are the first to become exhausted in soils (Glendinning, 2000).

As the Liebig's law of limiting states, "the nutrient least available is the first factor that restricts crop growth and yield formation" (Krishna, 2002), it is important to know the factors that affect nutrient dynamics and availability in soils as they influence nutrient management and the choice of tillage method. Nutrient availability, and thus transport of these nutrients to plant roots depend greatly on moisture content (Krishna, 2002), especially in arid and semi-arid regions where low-erratic rainfall events and high evaporation rates predominate. Under such conditions, conservation practices can improve crop productivity through nutrient cycling, organic matter accumulation and moisture conservation near the root zone.

No-tillage and residue retention both increase soil organic matter, which is desirable for water and nutrient conservation. Organic matter due to its negatively charged sites attracts cationic nutrients, and thereby reduces their losses through leaching. Surface runoff is also minimized in no-tilled soils due to better infiltrability. Since K release from crop residues is not microbially mediated, but facilitated by water leaching through crop residues (Yadvinder-Singh *et al*., 2005; Lupwayi *et al*., 2006a; Bhupinderpal-Singh & Rengel, 2007), reduced runoff and increased water infiltration under no-tillage can improve soil K (Ben Moussa-Machraoui *et al*., 2010). In addition, low mineralization and pronounced immobilization of nutrients (especially P and K) under no-tillage conserve appreciable amounts of these nutrients by temporarily reducing their availability and losses through leaching and fixation (Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007).

Some research studies across the globe indicated that nutrients like P and K, which are relatively immobile in the soil, are remarkably influenced by tillage, and that variations between different tillage methods are generally confined in the surface soil layer (Du Preez *et al*., 2001; Yadvinder-Singh *et al*., 2005; Lupwayi *et al*., 2006b; Limousin & Tessier, 2007;

Martin-Rueda *et al*., 2007; Thomas *et al*., 2007; Wright *et al*., 2007; Kotzé & Du Preez, 2008; López-Fando & Pardo, 2009; Houx III *et al*., 2011). Unlike N and S, which are highly mobile in the soil (Itanna, 2005; Yadvinder-Singh *et al*., 2005), P and K accumulate where they are placed. Stratification of these two nutrients has been shown to be more pronounced in the surface layers of no-tilled compared to conventionally tilled soil. This response is regarded to be the result of interacting factors, such as lack of soil disturbance and mixing, surface retention of crop residues and applied P and K fertilizers, uneven extraction of P and K by plant roots and their relative immobility in the soil (Lupwayi *et al*., 2006b; Martin-Rueda *et al*., 2007; Thomas *et al*., 2007; López-Fando & Pardo, 2009).

Mixing of soil and surface-placed crop residues as well as P and K fertilizers under conventional tillage increases the potential for fixation of these nutrients due to direct contact with soil colloids (Yadvinder-Singh *et al*., 2005). Rapid nutrient mineralization under conventional tillage may be inadequate to compensate for removal of these nutrients by crop roots (Martin-Rueda *et al*., 2007). As a result, their concentration in the upper layers of a tilled soil cannot be sustained over the long-term. Moreover, Limousin and Tessier (2007) after observing higher water infiltration and drainage under no-tillage compared to conventional tillage, reported that the loss of K in the latter was related more to chemical retention rather than leaching. Increased K stratification under the former system was attributed to high organic C, hence high K retention, and surface acidification that could have induced rapid mineral hydrolysis and liberation of K^+ ions. However, a decline in soil pH accentuates leaching losses of exchangeable base cations (Xu *et al*., 2002) and precipitation of P.

Unlike P and K, inconsistent results with regard to Ca, Mg and Na have been reported by a number of various studies. López-Fando and Pardo (2009) found that conservation tillage systems, especially no-tillage, can improve available Ca even in the deeper soil layers relative to conventional tillage, although the opposite was observed with available Mg. Thomas *et al*. (2007) also noted that no-tillage can influence the fate of exchangeable Mg and Na compared to conventional tillage, especially in the upper soil layer (0-10 cm), wherein none of the tillage treatments appeared to affect Ca. In contrast, Du Preez *et al*. (2001) indicated that the effect of tillage method on exchangeable Ca, Mg and Na was negligible or almost absent. Ten years later Kotzé and Du Preez (2008) noted on this particular soil a rise in Ca under tilled plots to 150 mm soil depth, below which both no-tillage and stubble mulch resulted in an accumulation of Ca. Furthermore, it was shown that no-tillage enhanced Mg contents not only in the surface soil, but throughout the studied soil layers. Houx III *et al*. (2011) showed no influence of tillage on Na. This variation between studies suggests that the distribution of these nutrients in the soil is influenced more by plant uptake and mineral dissolution than tillage method (Limousin & Tessier, 2007; Wright *et al*., 2007).

The impact of tillage and crop residue management on CEC can also vary depending on the nature of soil minerals and organic matter content. Limousin and Tessier (2007) emphasized that irrespective of tillage method, CEC can to a large extent be affected by soil pH. Surface acidification of no-tilled soil that usually prevails upon residue decomposition and nitrification of surface-placed ammonical fertilizers reduces CEC. High organic matter and associated pH-dependent charges play a prominent role in the decline of CEC (Limousin & Tessier, 2007; Thomas *et al*., 2007; López-Fando & Pardo, 2009). Conversely, Ben Moussa-Machraoui *et al*. (2010) showed higher organic matter accompanied by a corresponding increase in CEC in no-tillage compared to conventional tillage. Though soil pH was not determined in their study, they urged that CEC can be profoundly influenced by particle size distribution. Thus sandy soils (low in organic matter) have lower CEC than soils dominated by clay and organic matter.

Similarly, crop residue burning, due to its deleterious effects on organic matter and volatile nature of associated nutrients (C, N and S), can cause great oxidative losses of these nutrients into the atmosphere, leaving behind metal nutrients in residue ashes (Rengel, 2007). In essence, residue ashes are an effective source of K, Ca, Mg, Na and P (Xu *et al*., 2002; Rengel, 2007). According to Heard *et al*. (2006), these nutrients, especially P and K tend to be more concentrated (2-10 times) in the ashes than in the original crop residues. In a long-term wheat trial, straw burning showed a marked increase in K and P contents compared to where straw was not burned, while Ca, Mg and Na were least or not affected by straw disposal (Du Preez *et al*., 2001; Kotzé & Du Preez, 2008). Sharma and Mishra (2001) also showed that little proportions of P (22.2 %) and K (21.8 %) were lost during wheat straw burning. This can be credited to high volatilization temperatures of these nutrients which are seldom or not at all achieved during incomplete burning of crop residues (Sharma & Mishra, 2001; Heard *et al*., 2006).

Burning also increases the concentration as well as the solubility of nutrients in the soil. Such soluble nutrients become prone to erosion and leaching and consequently huge amounts can be lost out of the soil system. Unlike P, Ca as well as Mg, K leaches easily and quickly from the residue ashes into the soil (Menzies & Gillman, 2003). The downward movement of ash-derived K is so rapid that within two years of the field experiment in Cameroon, accumulation of this nutrient was more pronounced beyond 50 cm soil depth (Menzies & Gillman, 2003). Besides the solubility of ash-K, this can be a function of soil texture and the amount of percolating water.

Mbah and Nneji (2010) demonstrated that straw burning not only influences exchangeable cations and soil pH, but also increases CEC. However, during the course of their experiment, wavering results were noted in relation to the effects of straw disposal on CEC. In the first year, CEC was higher under unburned straw (surface mulch) compared to burned straw, but in the second year the burned treatments had a greater CEC than surface mulched plots. On the one hand, it can be deduced that the magnitude and direction of CEC depend essentially on the type of soil minerals present and the amount of organic matter (Ben Moussa-Machraoui *et al*., 2010), while on the other hand black C derived from burned plant biomass may have a robust effect on CEC (Liang *et al*., 2006). Black C provides large charge density and surface area of soil that contribute to high CEC (Liang *et al*., 2006).

As much as tillage and straw disposal influence macronutrients and CEC, weed control methods can potentially have an impact on these soil fertility indicators as well (Du Preez *et al*., 2001; Kotzé & Du Preez, 2008). Management practices that involve mechanical manipulation of the soil degrade organic matter and exposes nutrient-rich soil colloids to raindrop impact and erosive forces that may lead to nutrient load of water streams. In the same way application of anionic herbicides, which have a high affinity for cations (Hiller *et al*., 2007), can increase loss of these nutrients during leaching. Nevertheless, some herbicides contain substantial amounts of nutrients; therefore application of such herbicides can have a beneficial effect not only on weed control but also on soil fertility in general.

On account of inconsistent influence of crop residues on macronutrients and CEC in soil, the aim with this chapter was to evaluate the effects of different wheat residue management practices after 30 years on some soil macronutrients and CEC and to compare, where possible, the present results with those obtained in 1989 and 1999. The nutrients dealt with in this chapter are P, K, Ca, Mg and Na, since the fate of N and S was discussed earlier. Sodium is sometimes regarded as a micronutrient or beneficial nutrient; however, it was included in this chapter because it is also a basic cation.

5.2 Results and discussion

5.2.1 Extractable P

The summary of analyses of variance (Table 5.1) indicates that the methods of straw disposal, tillage and weeding had a significant influence on extractable P. However, the tillage systems showed a greater effect than weeding or straw disposal methods. The interactions between different treatments also showed a considerable effect on P.

Table 5.1 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on extractable P at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A	*	*	*			
B	*	*	*		*	*
AB	*	*	*	*	*	
C	*	*	*	*		
AC		*				
BC	*	*	*			*
ABC	*	*				

[a]A: straw disposal, B: tillage, C: weeding

Main effects

As displayed in Figure 5.1, higher P concentrations occurred in the burned plots compared to unburned plots across all the studied soil layers; however, significant differences were established only in the upper three soil layers. The mean P contents ranged from 23.43 to 25.43 mg kg^{-1} in the 0-50 mm, 22.58 to 26.20 mg kg^{-1} in the 50-100 mm and 22.85 to 25.09 mg kg^{-1} in the 100-150 mm soil layers. Similar results have been reported in the previous studies by Du Preez *et al*. (2001) as well as Kotzé and Du Preez (2008). In both studies, higher P contents were reported in the burned plots as compared to the unburned plots. However, in their study, Kotzé and Du Preez (2008) found that the differences between two methods of straw disposal were statistically insignificant.

Tillage methods affected extractable P significantly in the upper three and lower two soil layers (Figure 5.1). In the 0-50, 50-100 and 10-150 mm soil intervals, no-tilled plots contained the highest P (28.80, 29.46 and 28.79 mg kg^{-1} respectively), while the ploughed plots had the lowest P contents (21.55, 21.15 and 20.96 mg kg^{-1} respectively). In the mulched plots extractable P was intermediate, *viz.* 22.93 mg kg^{-1} in the 0-50 mm, 22.56 mg kg^{-1} in the 50-100 mm and 22.17 mg kg^{-1} in the 100-150 mm soil layers. In contrast, at 250-350 mm soil depth, the P content was higher in the ploughed plots (15.05 mg kg^{-1}) than in the mulched plots (12.55 mg kg^{-1}) and greater in the mulched plots than in no-tilled plots (10.72 mg kg^{-1}). The P in the 350-450 mm soil interval was highest in the mulched plots, followed in a decreasing order by ploughed plots and then no-tilled plots, *viz.* 6.60, 5.40

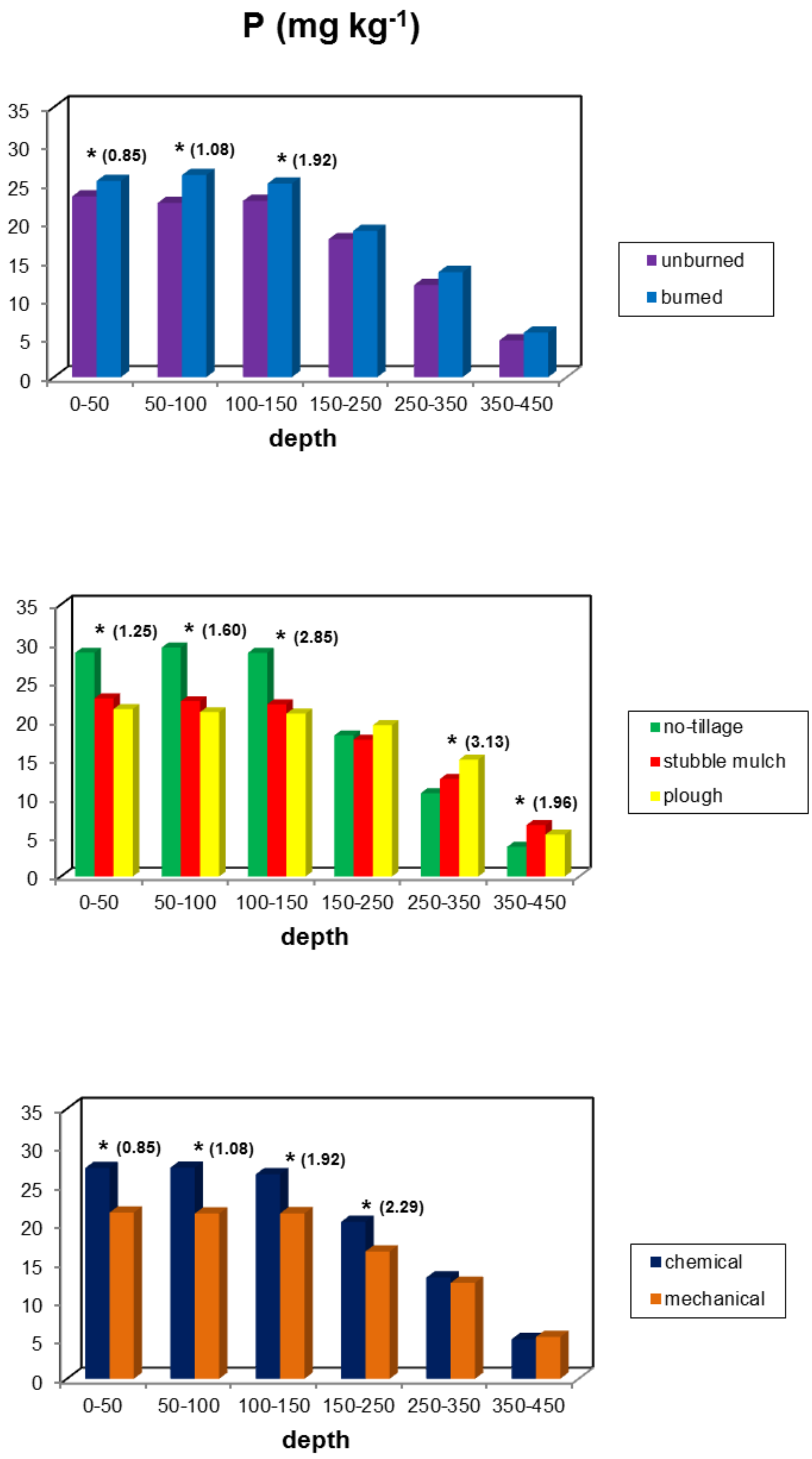

Figure 5.1 Effect of straw disposal, tillage and weed control methods on extractable P. LSD_T-values are shown where applicable.

and 3.82 mg kg^{-1} respectively. No significant difference was observed in the 150-250 mm soil layer; however, mouldboard ploughing slightly increased P compared to no-tillage and stubble mulch. These findings are sensible because in conservation techniques management of crop residues shows a strong effect primarily in the surface soil (Muukkonen *et al*., 2006). In the previous study by Du Preez *et al*. (2001), no-tilled and mulched plots had a higher P content than the ploughed plots to a depth of 150 mm. In the 150-250 mm soil layer, the no-tilled and ploughed plots had the same amount of P, but slightly lower than that of the mulched plots. Kotzé and Du Preez (2008) also reported that conservation (no-tillage and stubble mulch) tillage systems increased P more than mouldboard ploughing to a 250 mm soil depth, beyond which the ploughed plots contained a higher P than the no-tilled and mulched plots.

The influence of weeding methods on P was significant to a 250 mm soil depth with the chemically-weeded plots showing higher P contents when compared to mechanically-weeded plots (Figure 5.1). The P values varied from 21.54 to 27.32 mg kg^{-1} in the 0-50 mm, 21.41 to 27.37 mg kg^{-1} in the 50-100 mm, 21.44 to 26.50 mg kg^{-1} in the 100-150 mm and 16.49 to 20.33 mg kg^{-1} in the 150-250 mm intervals. Insignificant differences were registered in the deeper two soil layers. Chemical weeding also resulted in slightly higher P in the 250-350 mm soil layer compared to mechanical weeding. The trend was reversed in the 350-450 mm soil depth. Du Preez *et al*. (2001) also showed higher P in the chemically-weeded plots than in mechanically-weeded plots throughout the sampled soil layers. As displayed by Kotzé and Du Preez (2008), chemical weeding continued to increase extractable P when mechanical weeding served as a reference, though the significant increases were perceived only in the 0-50 and 150-250 mm soil layers. However, in the 350-450 mm soil interval, mechanically-weeded plots contained a slightly higher P content than the chemically-weeded plots as was the case in the present study.

Interactions

Data on the influence of interactions between different treatments on P are presented in Table 5.2. The summary of analyses of variance (Table 5.1) illustrates that the combinations between tillage systems and either methods of straw disposal or weeding had a stronger effect on P than the interaction between straw disposal and weeding methods.

At 0-50 and 50-100 mm soil intervals (LSD_T = 2.20 and 2.80 mg kg^{-1} respectively), the burned plots contained higher P than unburned plots despite the tillage method; however, no-tilled plots showed greater P concentrations than the mulched and ploughed plots. This was not the case in the 100-150 mm soil layer, where the plots that were unburned and not tilled had the highest P content (28.99 mg kg^{-1}) while unburned plots that were ploughed

Table 5.2 Effect of the interactions between straw disposal, tillage and weed control methods on extractable P (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	28.61	22.74	18.92	26.53	20.33
	Burned	28.98	23.13	24.18	28.10	22.76
Weeding	Chemical	29.42	29.12	23.41		
	Mechanical	28.18	16.75	19.69		
50-100 mm layer						
Straw	Unburned	27.57	22.00	18.17	24.96	20.20
	Burned	31.36	23.12	24.13	29.78	22.62
Weeding	Chemical	30.96	28.29	22.88		
	Mechanical	27.97	16.83	19.42		
100-150 mm layer						
Straw	Unburned	28.99	22.26	17.31	25.80	19.90
	Burned	28.59	22.08	24.61	27.20	22.98
Weeding	Chemical	29.40	27.58	22.53		
	Mechanical	28.18	16.75	19.39		
150-250 mm layer						
Straw	Unburned	20.34	16.97	16.31	20.83	14.92
	Burned	15.97	18.25	22.64	19.84	18.07
Weeding	Chemical	19.90	20.78	20.32		
	Mechanical	16.41	14.44	18.63		
250-350 mm layer						
Straw	Unburned	11.48	11.97	12.35	12.92	10.95
	Burned	9.96	13.12	17.74	13.31	13.90
Weeding	Chemical	10.80	14.40	14.16		
	Mechanical	10.64	10.70	15.94		
350-450 mm layer						
Straw	Unburned	3.36	6.74	4.22	5.17	4.37
	Burned	4.27	6.47	6.58	5.08	6.47
Weeding	Chemical	2.49	7.96	4.93		
	Mechanical	5.14	5.25	5.88		

had the lowest P content (17.31 mg kg^{-1}) with an LSD_T of 4.99 mg kg^{-1}. In both 150-250 and 250-350 mm soil layers, the highest P values (22.64 and 17.74 mg kg^{-1} respectively) were registered under straw burning combined with mouldboard ploughing, whereas the lowest P values (15.97 and 9.96 mg kg^{-1} respectively) were recorded when straw burning was combined with no-tillage with LSD_T values of 5.93 and 5.48 mg kg^{-1} respectively. There was no significant interaction between tillage and straw disposal in the 350-450 mm soil layer; nonetheless, the burned plots that were either ploughed or not tilled comprised a slightly higher P value than unburned plots that were either ploughed or not tilled. In the same soil layer conversely, the burned plots had a lower P content than unburned plots when mulched.

The combination of straw disposal and weeding methods significantly affected P only in the 50-100 mm soil layer (LSD_T = 2.04 mg kg^{-1}). In this soil layer, straw burning increased the concentration of P regardless of the weeding method, though the chemically-weeded plots had a higher P content than mechanically-weeded plots. Extractable P exhibited a similar trend in the 0-50, 100-150 and 250-350 mm soil layers, in spite of insignificant differences. In the 150-250 mm as well as 350-450 mm intervals the chemically-weeded unburned plots had the highest P values, whereas mechanically-weeded unburned plots had the lowest P values.

The combined use of tillage and weeding methods also had a marked influence on extractable P, particularly in the 0-50, 50-100, 100-150 and 350-450 mm soil layers (LSD_T = 2.20, 2.80, 4.99 and 3.43 mg kg^{-1} respectively), as can be seen in the summary of analyses of variance (Table 5.1). In the upper three soil layers, chemical weeding increased this nutrient more than mechanical weeding regardless of tillage system. However, the P values were high under no-tillage and decreased as tillage intensified. Though not significant, this trend manifested even in the 150-250 and 250-350 mm soil intervals. At these particular soil depths, in contrast, no-tilled plots contained lower P compared to the mulched and ploughed plots. Inconsistent effects of the tillage-weeding interaction were established in the 350-450 mm soil layer. Mechanically-weeded plots had a higher P content than the chemically-weeded plots when either ploughed or not tilled, while the chemically-weeded plots had a greater amount of P than mechanically-weeded plots when mulched.

In 1989 Du Preez *et al*. (2001) indicated significantly higher P content to 250 mm soil depth in the burned plots than in the unburned plots despite tillage or weeding method. They also reported that in the 0-50 and 50-150 mm soil layers, the no-tilled and mulched plots contained higher P than the ploughed plots irrespective of the methods of straw disposal or weeding. In 1999 Kotzé (2004) also found that across all the studied soil layers, the burned plots had higher P contents than the unburned plots regardless of tillage or weeding methods, though not always significant. In the 0-50 mm soil depth, the chemically-weeded plots had a higher P value than mechanically-weeded plots in spite of tillage or straw disposal method.

5.2.2 Exchangeable K

The summary of analyses of variance is given in Table 5.2. From this table, it can be seen that methods of straw disposal as well as tillage systems significantly influenced exchangeable K, whereas the weeding methods showed no significant effect on K in any of the six soil layers. The combinations between different treatments also did not affect K significantly.

Table 5.3 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on exchangeable K at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A	*	*	*	*	*	*
B	*	*				*
AB						
C						
AC						
BC						
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

As mentioned above, methods of straw disposal affected K significantly in all the sampled soil layers (Figure 5.2). These results are consistent with the findings of the previous studies (Du Preez *et al*., 2001; Kotzé & Du Preez, 2008). In both studies, higher K contents were observed in the burned compared to unburned plots in all the sampled soil layers.

The effect of different tillage systems on exchangeable K was significant only in the 0-50, 50-100 and 350-450 mm soil depths (Figure 5.2). At the soil depths of 0-50 and 50-100 mm, the no-tilled plots contained the most K (428 and 336 mg kg^{-1} respectively) followed by the mulched plots (325 and 261 mg kg^{-1} respectively) and then the ploughed plots (203 and 221 mg kg^{-1} respectively). A similar pattern persisted in the 100-150 mm soil interval, even

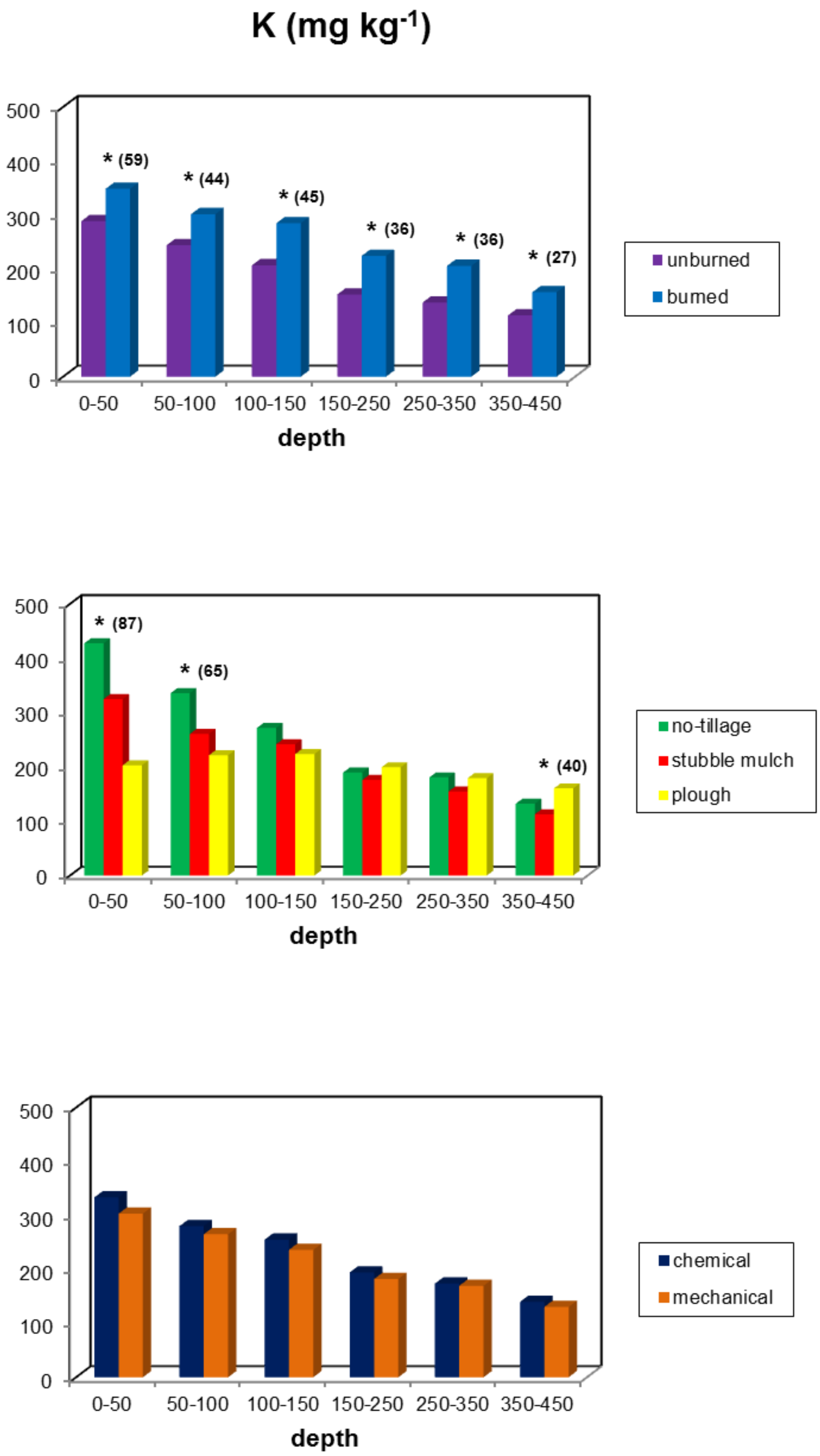

Figure 5.2 Effect of straw disposal, tillage and weed control methods on exchangeable K. LSD_T-values are shown where applicable.

though the difference was not significant. Conversely, in the 350-450 mm soil depth, the trend was significantly reversed. The K concentration in this soil layer ranged from 113 mg kg^{-1} in the mulched plots to 160 mg kg^{-1} in the ploughed plots. An intermediate value of 132 mg kg^{-1} K was recorded in no-tilled treatments. Potassium exhibited the same behaviour in the 150-250 and 250-350 mm soil layers. No significant effect was observed in either of the two soil layers as a result of tillage. Similarly, Du Preez *et al*. (2001) (0-50 and 50-150 mm soil layers) as well as Kotzé and Du Preez (2008) (0-50 and 50-100 mm soil depths) found the highest K in the no-tilled plots followed by the mulched plots and then the ploughed plots. Below 150 mm soil depth, the ploughed plots comprised of higher K than the no-tilled or mulched plots.

Further inspection of Figure 5.2 shows that none of the weeding methods had a significant effect on exchangeable K. Nevertheless, chemical weeding slightly elevated this nutrient more than mechanical weeding in all the six soil layers. These results confirm the findings of the previous studies (Du Preez *et al*., 2001; Kotzé & Du Preez, 2008). However, in 1999 K differed significantly between the two weeding methods in the 0-50 mm soil depth (Kotzé & Du Preez, 2008). The opposite was perceived in the 250-350 mm soil interval where mechanically-weeded plots had a slightly higher K than the chemically-weeded plots.

Interactions

Data on the interactive effects of different field treatments on K are shown in Table 5.4. As indicated in the summary of analyses of variance (Table 5.3), there were no significant interactions observed in relation to K; however, the combination of straw disposal with either tillage or weeding methods showed some interesting trends. Across all the sampled soil depths, the burned plots had a slightly higher K than unburned plots regardless of tillage regime or weeding method. However, highest K values were recorded under no-tillage as well as under chemical weeding. Tillage practices combined with weeding methods showed insignificant and variable effects on K.

In spite of insignificant interactions reported in this study, Du Preez *et al*. (2001) as well as Kotzé and Du Preez (2008) reported more or less the same trends with regard to the interactions between different treatments. In the top 250 mm soil depth, Du Preez *et al*. (2001) found higher K in the burned plots than in the unburned plots regardless of tillage practice or weeding method used. Similarly, the K of the no-tilled plots was higher than that of the mulched or ploughed plots in the upper 150 mm soil depth despite the method of straw disposal or weeding. The opposite was recorded in the 150-250 mm layer, wherein the amount of K was found to be higher in the ploughed plots when compared to the mulched and no-tilled plots. Chemical weeding also increased K, but only in the upper soil interval

Table 5.4 Effect of the interactions between straw disposal, tillage and weed control methods on exchangeable K (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	371	302	193	290	287
	Burned	485	347	213	377	319
Weeding	Chemical	494	314	193		
	Mechanical	362	335	213		
50-100 mm layer						
Straw	Unburned	294	232	205	246	241
	Burned	378	289	238	314	289
Weeding	Chemical	350	271	219		
	Mechanical	321	250	224		
100-150 mm layer						
Straw	Unburned	217	196	206	217	196
	Burned	326	287	241	293	276
Weeding	Chemical	270	274	221		
	Mechanical	273	209	226		
150-250 mm layer						
Straw	Unburned	151	130	176	159	146
	Burned	228	222	222	230	218
Weeding	Chemical	190	202	191		
	Mechanical	189	150	207		
250-350 mm layer						
Straw	Unburned	137	122	154	143	132
	Burned	225	187	204	204	207
Weeding	Chemical	172	174	175		
	Mechanical	190	136	183		
350-450 mm layer						
Straw	Unburned	105	94	141	119	108
	Burned	159	131	180	161	152
Weeding	Chemical	132	131	156		
	Mechanical	132	94	165		

(0-50 mm), particularly when no-tillage or stubble mulch combined with straw burning were applied. Irrespective of tillage or weeding method, Kotzé and Du Preez (2008) also observed greater K contents in the upper two to three soil layers of the burned plots compared to unburned plots, though the differences were not always significant. They also indicated that the chemically-weeded burned plots had the highest K content while mechanically-weeded unburned plots had the lowest K concentration.

5.2.3 Exchangeable Ca

The summary of analyses of variance (Table 5.5) shows that exchangeable Ca was affected by methods of tillage and straw disposal, respectively. There were no significant effects observed in any of the six layers as a result of the weeding methods. The only significant interactions were recorded in the 50-100 mm soil layer between straw disposal methods and weeding as well as tillage and weeding methods.

Table 5.5 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on exchangeable Ca at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A	*					*
B		*			*	*
AB						
C						
AC		*				
BC		*				
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

The Ca of the unburned plots was higher than that of the burned plots in all the studied soil intervals; however, significant differences were recorded only in the 0-50 and 350-450 mm soil layers (Figure 5.3). The amount of Ca ranged from 870 to 1195 mg kg^{-1} in the 0-50 mm and from 983 to 1185 mg kg^{-1} in the 350-450 mm soil layers.

As indicated in Figure 5.3, methods of tillage affected exchangeable Ca significantly in the 50-100, 250-350 and 350-450 mm soil layers. In these particular soil layers, no-tillage resulted in the highest Ca values (1307, 1227 and 1294 mg kg^{-1} respectively), while the lowest Ca values (874, 877 and 941 mg kg^{-1} respectively) were found under stubble mulch tillage. Intermediate values of 1061, 936 and 1018 mg Ca kg^{-1} respectively were recorded in the ploughed plots. Although no significant differences could be observed between the tillage systems in the other three soil layers (0-50, 100-150 and 150-250 mm), a similar trend manifested even in these soil layers, where the highest Ca contents were found in no-tilled plots followed by ploughed plots and then the mulched plots.

Weeding methods did not cause any significant effect on Ca in any of the studied soil layers (Figure 5.3). However, unlike P and K, the Ca content of the chemically-weeded plots was slightly lower than that of mechanically-weeded plots.

In contrast, Du Preez *et al*. (2001) indicated that none of the applied field treatments influenced Ca after 11-12 years of this trial. Kotzé and Du Preez (2008) after 20 years also reported insignificant effects and lack of consistency on Ca as a result of the methods of straw disposal. However, some trends evolved between the three tillage systems applied, although a significant difference was noted only in the 250-350 mm soil layer. In this soil layer, the no-tilled plots had the highest Ca followed by the mulched plots and then the ploughed plots. A similar pattern was also reported in the 350-450 mm soil depth. In the upper three soil intervals, the ploughed plots contained the highest Ca while the mulched plots had the lowest Ca content. The intermediate values of Ca were found in the no-tilled plots. This was not the case after 30 years of this trial. As found in this study, Kotzé and Du Preez (2008) observed a similar response of Ca to the weeding methods except in the 0-50 and 100-150 mm layers where higher Ca contents were recorded in the chemically-weeded plots when compared to mechanically-weeded plots.

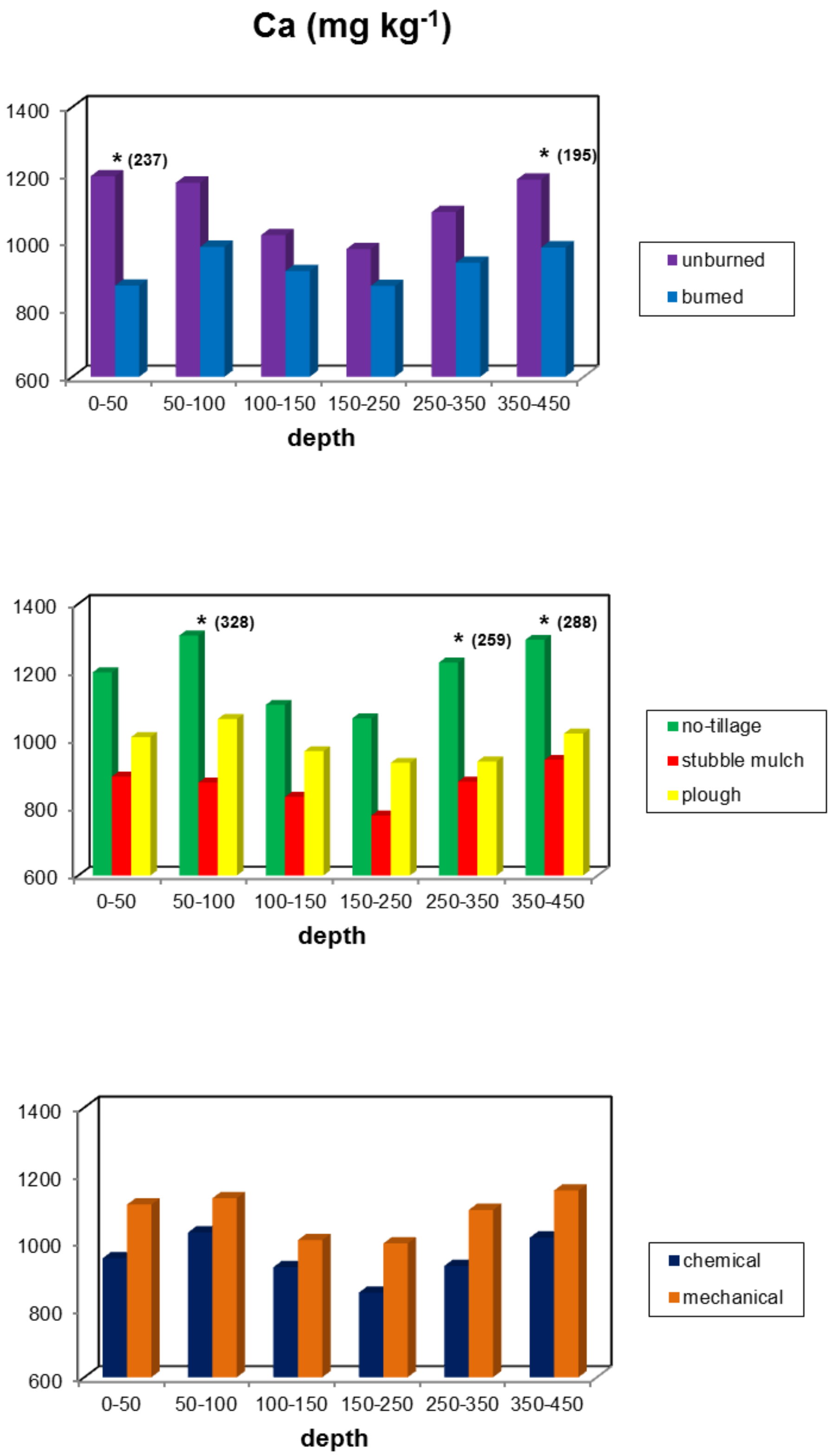

Figure 5.3 Effect of straw disposal, tillage and weed control methods on exchangeable Ca. LSD_T-values are shown where applicable.

Interactions

Data on the interactions between different treatments on exchangeable Ca are given in Table 5.6. As illustrated in the summary of analyses of variance (Table 5.5), significant interactions were perceived only in the 50-100 mm soil layer between weeding methods and either straw disposal or tillage practices. The concentration of Ca in this soil layer ranged from 924 mg kg^{-1} in mechanically-weeded burned plots to 1338 mg kg^{-1} in mechanically-weeded unburned plots with an LSD_T of 419 mg kg^{-1}. In the same soil layer, no-tillage when combined with chemical weeding resulted in a greater accumulation of Ca (1482 mg kg^{-1}) than stubble mulch (814 mg kg^{-1}) and mouldboard ploughing (792 mg kg^{-1}), while mouldboard ploughing increased Ca (1330 mg kg^{-1}) more than no-tillage (1131 mg kg^{-1}) and stubble mulch (933 mg kg^{-1}) when combined with mechanical weeding with an LSD_T of 575 mg kg^{-1}. There were no significant interactions on exchangeable Ca in the other five soil layers as a result of the treatment combinations.

According to Kotze (2004), no significant interactions could be noted in any of the six soil layers. However, unburned-ploughed plots were found to contain the highest Ca contents, while unburned-mulched plots had the lowest Ca to a soil depth of 150 mm, below which there were no clear trends.

Table 5.6 Effect of the interactions between straw disposal, tillage and weed control methods on exchangeable Ca (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	1293	1060	1231	1041	1349
	Burned	1104	723	784	865	876
Weeding	Chemical	1289	792	778		
	Mechanical	1108	991	1238		
50-100 mm layer						
Straw	Unburned	1270	1022	1235	1013	1338
	Burned	1343	725	887	1046	924
Weeding	Chemical	1482	814	792		
	Mechanical	1131	933	1330		
100-150 mm layer						
Straw	Unburned	1057	918	1085	911	1130
	Burned	1148	745	847	942	884
Weeding	Chemical	1144	821	815		
	Mechanical	1061	842	1117		
150-250 mm layer						
Straw	Unburned	1075	818	1043	828	1129
	Burned	1050	736	821	874	864
Weeding	Chemical	1039	748	766		
	Mechanical	1087	806	1098		
250-350 mm layer						
Straw	Unburned	1260	985	1021	944	1233
	Burned	1194	769	851	917	959
Weeding	Chemical	1173	809	809		
	Mechanical	1281	944	1063		
350-450 mm layer						
Straw	Unburned	1383	1066	1106	1025	1346
	Burned	1205	815	929	1004	963
Weeding	Chemical	1302	891	850		
	Mechanical	1286	991	1185		

5.2.4 Exchangeable Mg

The summary of analyses of variance (Table 5.7) presents the significant effects of different treatments on exchangeable Mg. Inspection of Table 5.7 indicates that only tillage practices had a significant influence on Mg. Neither methods of straw disposal nor weeding methods showed a substantial effect on Mg. The effects of different treatment combinations were also not significant.

Table 5.7 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on exchangeable Mg at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A						
B	*	*	*	*	*	
AB						
C						
AC						
BC						
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Unlike Ca, the concentration of Mg was higher in the burned plots than unburned plots to a soil depth of 350 mm despite insignificant differences (Figure 5.4). The trend was reversed in the 350-450 mm soil layer. In this soil layer, unburned plots contained a slightly higher Mg than the burned plots.

As stated earlier in this section, tillage systems showed a marked effect on exchangeable Mg to a soil depth of 350 mm (Figure 5.4). The highest Mg contents were recorded under no-tillage followed by stubble mulch and then mouldboard ploughing. Exchangeable Mg reflected a similar behaviour in the 350-450 mm soil layer, though the difference was not significant.

The weeding methods, like methods of straw disposal, had no significant influence on Mg in any of the studied soil layers (Figure 5.4). Even so, chemical weeding slightly raised Mg compared to mechanical weeding.

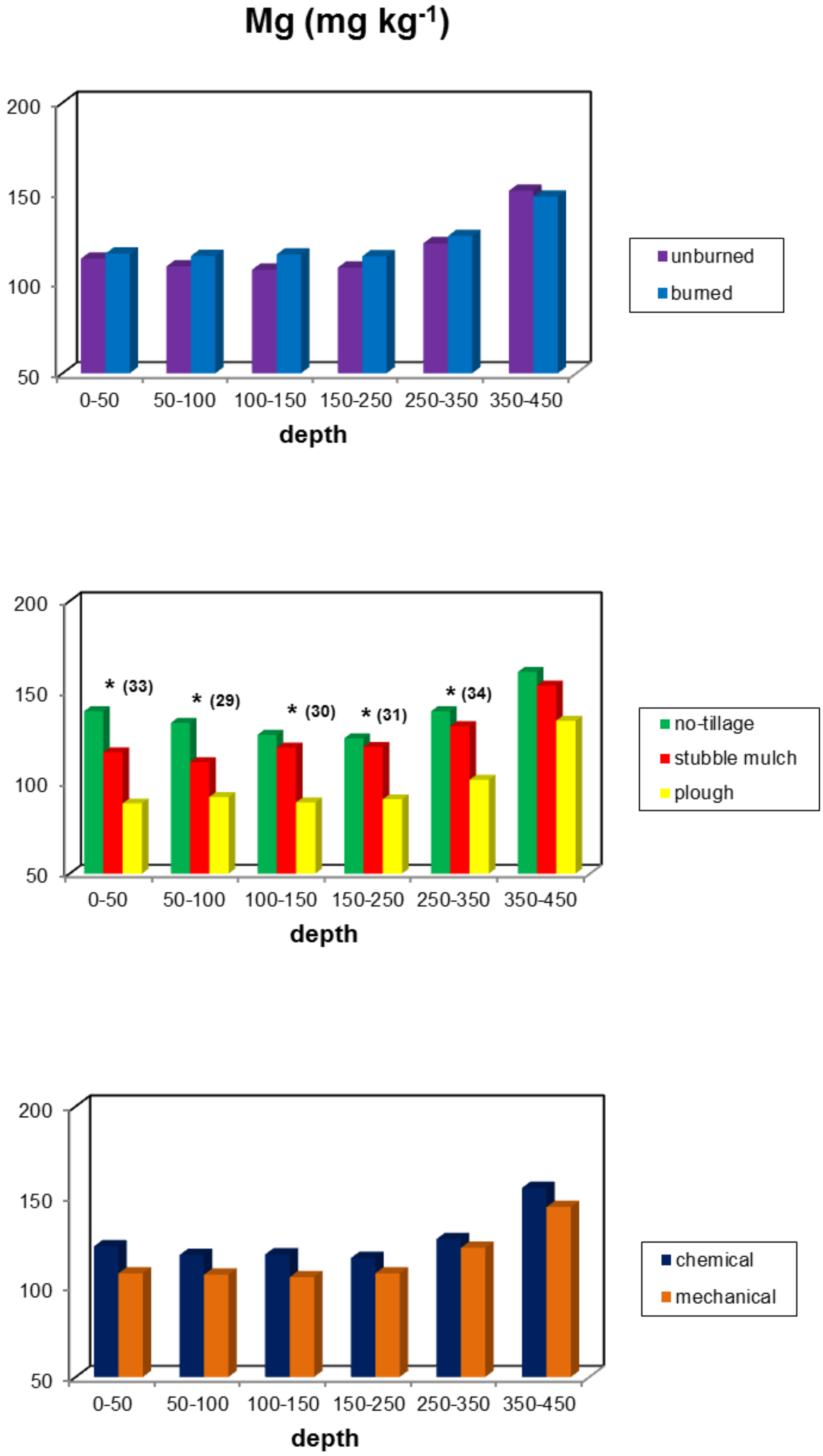

Figure 5.4 Effect of straw disposal, tillage and weed control methods on exchangeable Mg. LSD_T-values are shown where applicable.

As with Ca, all the applied treatments did not show any effect on Mg after 11-12 years of this trial (Du Preez *et al*., 2001). After 20 years however, some trends started to emerge between different treatments, although not always significant (Kotzé & Du Preez, 2008). In the upper and deeper three soil layers Mg was found to be slightly higher in the burned plots than in the unburned plots. The reverse was noted in the soil depths of 50-100 and 100-150 mm. They also obtained higher Mg in the no-tilled plots when compared to the mulched or ploughed plots. However, in consideration of the weeding methods, the present results contradict with those recorded in 1999 (Kotzé & Du Preez, 2008), especially in the lower three soil layers. At these soil depths, they found that mechanical weeding tended to increase Mg more than chemical weeding.

Interactions

The effects of different treatment interactions on exchangeable Mg are presented in Table 5.8. From the summary of analyses of variance (Table 5.7), it can be seen that no significant interactions could be measured with regard to Mg throughout the soil profile. Some trends emerged however, between methods of straw disposal and weeding. The burned plots had a slightly higher Mg than the unburned plots in the upper four soil layers (to a 250 mm soil depth) regardless of the weeding method applied.

In spite of insignificant differences, some interesting trends also evolved as a result of the combinations between tillage and straw disposal methods. In the upper three and lower two soil layers, no-tillage increased Mg contents more than stubble mulch or mouldboard ploughing regardless of the method of straw disposal. However, at 150-250 mm soil depth, the maximum values of Mg were measured under no-tillage combined with no-burning as well as under stubble mulch combined with straw burning, while the interactive use of ploughing and no-burning resulted in the lowest Mg.

As it was established in this study, Mg was not affected by any of the combinations between different treatments in 1989 (Du Preez *et al*., 2001). Conversely, Kotzé and Du Preez (2008) noted a significant interaction between tillage and weeding methods only in the uppermost soil layer. At this soil depth, the chemically-weeded no-tilled plots were shown to have the highest Mg content, whereas the chemically-weeded ploughed plots had the lowest Mg content.

Table 5.8 Effect of the interactions between straw disposal, tillage and weed control methods on exchangeable Mg (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	139	121	81	122	105
	Burned	140	113	96	123	110
Weeding	Chemical	155	114	98		
	Mechanical	123	120	79		
50-100 mm layer						
Straw	Unburned	133	113	82	117	101
	Burned	133	110	102	118	112
Weeding	Chemical	141	115	97		
	Mechanical	125	108	87		
100-150 mm layer						
Straw	Unburned	123	115	84	117	98
	Burned	130	123	95	119	113
Weeding	Chemical	124	132	98		
	Mechanical	129	107	80		
150-250 mm layer						
Straw	Unburned	127	113	86	114	103
	Burned	122	127	96	118	112
Weeding	Chemical	119	130	99		
	Mechanical	130	110	83		
250-350 mm layer						
Straw	Unburned	135	133	98	129	115
	Burned	144	129	105	123	129
Weeding	Chemical	131	138	111		
	Mechanical	148	125	93		
350-450 mm layer						
Straw	Unburned	164	159	131	162	141
	Burned	158	148	138	148	148
Weeding	Chemical	160	170	135		
	Mechanical	162	137	133		

5.2.5 Exchangeable Na

Sodium is not a macronutrient; however, due to its importance in soil fertility as well as for comparison purposes, this nutrient was included in the present study. As illustrated in the summary of analyses of variance (Table 5.9), the exchangeable fraction of Na was influenced more by tillage and weeding methods than the methods of straw disposal. The only significant interaction was observed between method of straw disposal and tillage.

Table 5.9 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on exchangeable Na at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A						*
B	*	*	*	*	*	*
AB		*				*
C	*	*	*	*	*	*
AC						
BC						
ABC				*		*

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Methods of straw disposal had a significant effect on Na only in the 350-450 mm soil layer (Figure 5.5). The mean Na content in this soil depth ranged from 22.22 mg kg^{-1} in the burned plots to 26.07 mg kg^{-1} in the unburned plots. There were no significant effects to a soil depth of 350 mm; however, unburned plots had a slightly higher Na than the burned plots.

As mentioned at the beginning of this section, tillage systems significantly influenced this nutrient across all the sampled soil depths (Figure 5.5). In all the six soil layers, the highest concentration of Na was measured under no-tillage, followed by mouldboard ploughing and then stubble mulch.

Similarly, the weeding methods also showed a significant effect on exchangeable Na throughout the soil profile (Figure 5.5). The differences in Na values obtained after 30 years of this trial indicated that mechanically-weeded plots had significantly lower Na contents than the chemically-weeded plots.

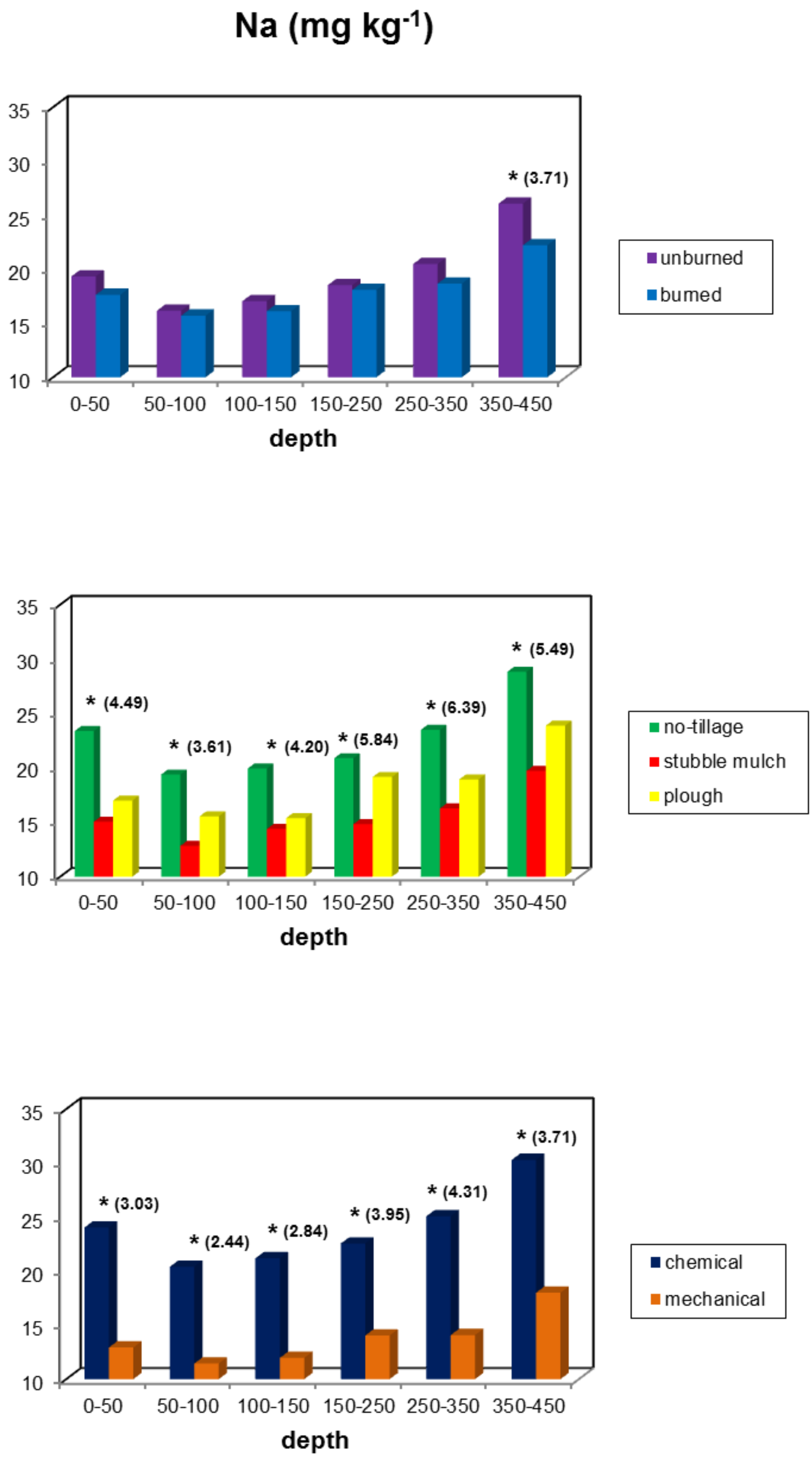

Figure 5.5 Effect of straw disposal, tillage and weed control methods on exchangeable Na. LSD_T-values are shown where applicable.

Interactions

The effects of different treatment combinations on exchangeable Na are summarized in Table 5.10. The only significant interactions were measured between tillage and straw disposal in the 50-100 and 350-450 mm soil layers (LSD_T = 6.32 and 9.61 mg kg^{-1} respectively), as can be seen in the summary of analyses of variance (Table 5.9). The burned and no-tilled plots had the highest Na (21.33 mg kg^{-1}) while the burned and mulched plots contained the lowest amount of this nutrient (12.11 mg kg^{-1}) in the 50-100 mm soil layer. At 350-450 mm soil depth, no-tillage (29.78 mg kg^{-1}) accumulated Na more than stubble mulch (18.78 mg kg^{-1}) and mouldboard ploughing (18.11 mg kg^{-1}) when straw was burned. In the same layer, in contrast, the ploughed plots (29.67 mg kg^{-1}) had the highest Na followed by no-tilled plots (27.89 mg kg^{-1}) and then the mulched plots (20.67 mg kg^{-1}) when the wheat straw was not burned. A similar pattern was reflected in the 150-250 mm soil interval despite insignificant differences. At the soil depths of 0-50, 100-150 and 250-350 mm, no-tilled plots contained a slightly higher Na content than the mulched and ploughed plots, irrespective of straw disposal method. However, the burned plots showed higher Na contents compared to the unburned plots.

A further inspection of the summary of analyses of variance (Table 5.9) clearly indicates that no significant interactions were measured between weeding and tillage or straw disposal. Nevertheless, chemical weeding increased Na concentration in all the six soil layers more than mechanical weeding, regardless of tillage or straw disposal. The no-tilled plots had a higher Na content than the ploughed and mulched plots, while the unburned plots contained higher Na than the burned plots.

Neither the main treatments nor their interactions affected exchangeable Na in 1989/1990 (Du Preez *et al*., 2001) and 1999 (Kotzé & Du Preez, 2008). However, the 30 year results, which are reported in this study, revealed that management of wheat residues not only showed some interesting trends but had a marked influence on exchangeable Na. The response of Na to the applied treatments validates the fact that soil fertility indicators may become evident after a couple of decades depending on local climatic and soil conditions (Bhupinderpal-Singh & Rengel, 2007).

Table 5.10 Effect of the interactions between straw disposal, tillage and weed control methods on exchangeable Na (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	25.11	14.44	18.44	26.30	12.37
	Burned	21.67	15.67	15.56	21.78	13.48
Weeding	Chemical	31.11	20.00	21.00		
	Mechanical	15.67	10.11	13.00		
50-100 mm layer						
Straw	Unburned	17.44	13.56	17.44	20.89	11.41
	Burned	21.33	12.11	13.67	19.93	11.48
Weeding	Chemical	23.67	17.56	20.00		
	Mechanical	15.11	8.11	11.11		
100-150 mm layer						
Straw	Unburned	20.22	14.00	16.89	22.37	11.70
	Burned	19.67	14.78	13.89	20.00	12.22
Weeding	Chemical	23.78	20.00	19.78		
	Mechanical	16.11	8.78	11.00		
150-250 mm layer						
Straw	Unburned	19.00	14.44	22.11	24.00	13.04
	Burned	22.78	15.22	16.22	21.11	15.04
Weeding	Chemical	24.67	20.44	22.56		
	Mechanical	17.11	9.22	15.78		
250-350 mm layer						
Straw	Unburned	22.22	18.11	21.11	27.11	13.85
	Burned	24.78	14.44	16.77	23.04	14.30
Weeding	Chemical	27.44	23.22	24.56		
	Mechanical	19.56	9.33	13.33		
350-450 mm layer						
Straw	Unburned	27.89	20.67	29.67	33.04	19.11
	Burned	29.78	18.78	18.11	27.56	16.89
Weeding	Chemical	33.78	27.67	29.44		
	Mechanical	23.89	11.78	18.33		

5.2.6 CEC

Tillage and weeding methods had a significant influence on CEC throughout the sampled soil layers as can be witnessed in the summary of analyses of variance (Table 5.11). In contrast, methods of straw disposal did not show any effect on CEC. Different treatment interactions influenced CEC significantly throughout the soil profile.

Table 5.11 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on CEC at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A						
B	*	*	*	*	*	*
AB	*	*	*	*	*	*
C	*	*	*	*	*	*
AC	*	*	*	*	*	*
BC	*	*	*	*	*	*
ABC	*	*	*	*	*	

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Methods of straw disposal did not affect the CEC of this Avalon soil in any of the six soil layers (Figure 5.6). However, unburned straw showed a slightly higher CEC in the upper two and lowermost soil layers compared to the burned straw. In the other three soil layers (from 100 to 350 mm), straw burning showed a slightly higher CEC more than no-burning.

As illustrated in Figure 5.9, there were significant differences in CEC among the applied tillage systems. Across all the six soil layers, the highest CEC values were measured under no-tillage followed by stubble mulch and then mouldboard ploughing. In contrast to that, CEC values in the 350-450 mm soil layer were similar under stubble mulch and ploughing.

Similarly, the weeding methods also influenced CEC significantly throughout the soil profile (Figure 5.6), with chemically-weeded plots having higher CEC values compared to mechanically-weeded plots.

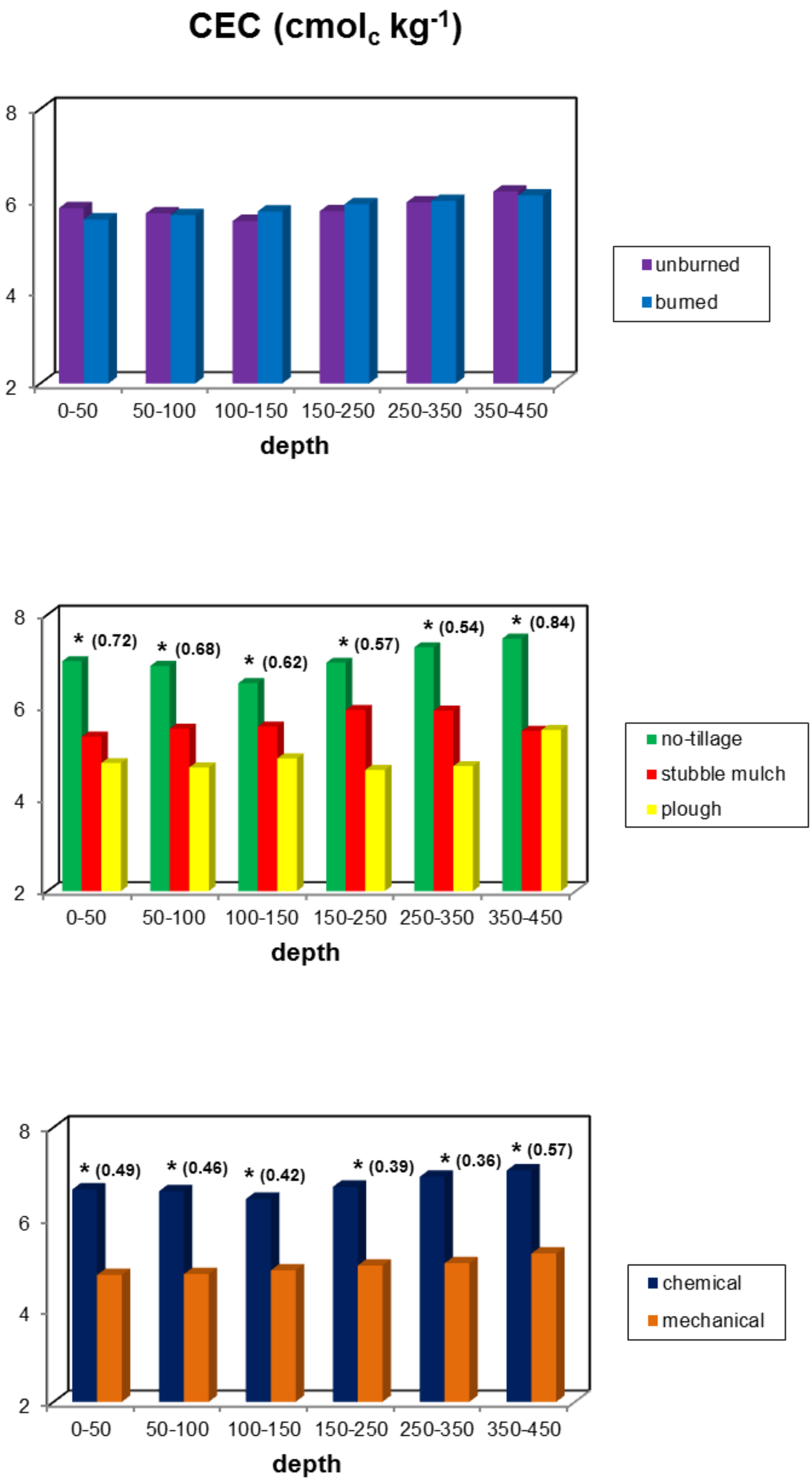

Figure 5.6 Effect of straw disposal, tillage and weed control methods on CEC. LSD_T-values are shown where applicable.

Interactions

Data indicating the interactions between different treatments on CEC are presented in Table 5.12. As demonstrated in the summary of analyses of variance (Table 5.11), different treatment combinations affected the CEC significantly in all the six soil layers. In the upper two (0-50 and 50-100 mm with LSD_T values of 1.27 and 1.18 $cmol_c$ kg^{-1} respectively) and lower two (250-350 and 350-450 mm with LSD_T values of 0.94 and 1.47 $cmol_c$ kg^{-1} respectively) soil layers, the no-tilled plots had higher CEC values than the mulched and ploughed plots, especially when wheat straw was burned. At both middle soil intervals (100-150 and 150-250 mm), the highest CEC was observed under no-tillage combined with straw burning, while the lowest CEC values were recorded under mouldboard ploughing combined with straw burning with LSD_T values of 1.09 and 1.00 $cmol_c$ kg^{-1}, respectively.

Despite the weeding method, no-tillage also increased CEC more than stubble mulch and mouldboard ploughing, with the chemically-weeded plots showing higher CEC values when compared to mechanical weeding except in the soil layer of 100-150 mm. In this soil layer, the no-tilled plots conceded a higher CEC than the mulched or ploughed plots when mechanical weeding was applied, whereas the mulched plots tended to have a greater CEC than the no-tilled or ploughed plots when chemical weeding was used. The LSD_T values for various soil layers, from the top to the deeper layers, are 1.27, 1.18, 1.09, 1.00, 0.94 and 1.47 $cmol_c$ kg^{-1} respectively.

The interaction between weeding and straw disposal also showed invariable effects on CEC throughout the studied soil profile. Regardless of the methods of straw disposal, the chemically-weeded plots had higher CEC values than mechanically-weeded plots with LSD_T values of 0.92 $cmol_c$ kg^{-1} in the 0-50 mm, 0.86 $cmol_c$ kg^{-1} in the 50-100 mm, 0.80 $cmol_c$ kg^{-1} in the 100-150 mm, 0.73 $cmol_c$ kg^{-1} in the 150-250 mm, 0.68 $cmol_c$ kg^{-1} in the 250-350 mm, and 1.07 $cmol_c$ kg^{-1} in the 350-450 mm soil depths. However, as with the combination of tillage and straw disposal, higher CEC values were detected in the burned rather than unburned plots. None of the previous studies on this trial evaluated the influence of different wheat residue management on CEC; therefore comparison in this regard is impossible.

In general, according to Du Preez *et al*. (2001), stratification of P and K manifested strongly within 11-12 years of this trial, while Ca, Mg and Na were virtually absent. Kotzé and Du Preez (2008) indicated that besides P and K, the response of Ca and Mg to different field treatments started to emerge only between 11-12 and 20 years. Exchangeable Na was still almost absent. The results of this study however, revealed that different wheat residue management practices to some extent continued to influence the distribution of these nutrients, including CEC.

Table 5.12 Effect of the interactions between straw disposal, tillage and weed control methods on CEC ($cmol_c\ kg^{-1}$)

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	6.34	5.84	5.32	6.41	5.25
	Burned	7.64	4.87	4.23	6.87	4.29
Weeding	Chemical	7.21	6.59	6.12		
	Mechanical	6.77	4.11	3.44		
50-100 mm layer						
Straw	Unburned	6.06	5.96	5.13	6.30	5.14
	Burned	7.71	5.09	4.24	6.91	4.45
Weeding	Chemical	7.06	6.61	6.15		
	Mechanical	6.72	4.44	3.22		
100-150 mm layer						
Straw	Unburned	5.22	5.99	5.44	5.91	5.18
	Burned	7.81	5.16	4.31	6.96	4.56
Weeding	Chemical	6.40	6.61	6.30		
	Mechanical	6.62	4.54	3.46		
150-250 mm layer						
Straw	Unburned	6.11	6.23	4.95	6.36	5.16
	Burned	7.80	5.63	4.31	7.04	4.79
Weeding	Chemical	6.94	6.91	6.26		
	Mechanical	6.98	4.95	3.00		
250-350 mm layer						
Straw	Unburned	6.41	6.20	5.27	6.61	5.31
	Burned	8.17	5.64	4.16	7.23	4.75
Weeding	Chemical	7.47	6.95	6.34		
	Mechanical	7.12	4.89	3.08		
350-450 mm layer						
Straw	Unburned	6.55	5.46	6.57	6.62	5.77
	Burned	8.41	5.49	4.42	7.50	4.71
Weeding	Chemical	7.66	7.00	6.52		
	Mechanical	7.29	3.96	4.47		

Straw burning increased P, K and Mg more than no-burning, while no-burning resulted in a substantial accumulation of Ca and Na when compared to straw burning. No trends or significant effects on CEC were established as a result of the methods of straw disposal. In the study conducted by Mbah and Nneji (2010), which lasted for two cropping seasons in a Typic Haplustalt, it was found that straw burning generally increased these nutrients more than no-burning (surface mulch) except for P and Na which were higher in the surface mulched treatments as opposed to the burned plots. The effects of these two treatments on CEC were not consistent for both cropping seasons. As displayed in some studies (Xu *et al*., 2002; Rengel, 2007), crop residue ashes are an important source of these nutrients, and due to their (P, K, Ca, Mg and Na) high volatilization temperatures (Sharma & Mishra, 2001; Heard *et al*., 2006), accumulation of all these nutrients would be expected in the burned rather than unburned plots. However, crop demand for nutrients, which varies with plant type, variety and species, may contribute to the distribution of these nutrients in the soil (Limousin &Tessier, 2007). The efficiency of the extracting methods can also be attributable to the different results between studies, especially for P, which in the present study was extracted using the Olsen method while in their study (Mbah & Nneji, 2010) the Bray II was employed.

The applied tillage systems influenced P, K, Ca, Mg and Na to various soil depths. No-tillage increased P and K to a soil depth of 150 mm as well as Ca, Mg and Na to 450 mm soil depth when compared to the other two tillage methods applied. Several researchers (Limousin & Tessier, 2007; Martin-Rueda *et al*., 2007; Thomas *et al*., 2007; López-Fando & Pardo, 2009; Ben Moussa-Machraoui *et al*., 2010) also found higher concentrations of P and K in the surface layers of no-tilled soils when compared to cultivated soils. However, with regard to Ca, Mg and Na, differences between studies occurred, presumably because the distribution of the latter three in soils seem to be affected more by soil properties and to a certain degree by plant uptake than tillage practices (Limousin & Tessier, 2007; Wright *et al*., 2007). In the current study though, the effects of tillage practices on the three cations were evident. If a trend regarding these three cations is to be followed since the initiation of this trial, it could be seen that at early stages of this long-term wheat trial these nutrients were slightly or not at all influenced by the applied tillage methods until to date when they all show a significant response to the assigned field treatments. Therefore this is attributed to different tillage practices that have been applied consecutively for 30 years.

Numerous researchers (Schomberg *et al*., 1994; Lupwayi *et al*., 2006b; Limousin & Tessier, 2007; Martin-Rueda *et al*., 2007; Thomas *et al*., 2007; López-Fando & Pardo, 2009; Ben Moussa-Machraoui *et al*., 2010) have indicated that surface stratification of P and K in no-tillage as opposed to mouldboard ploughing is a function of surface application of these nutrients from fertilizers and crop residues accompanied by lack of soil disturbance. This is logical since substantial quantities of total plant K and possibly P usually accumulate in the plant straw (Bhupinderpal-Singh & Rengel, 2007). Schomberg *et al*. (1994) added that the high concentrations of crop residues in the surface of no-tilled soil increases the shielding effect against P adsorption on soil colloids and thereby promoting the build-up of P in the latter system. Furthermore, Ben Moussa-Machraoui *et al*. (2010) pointed out that reduced erosion and runoff following surface mulching in no-tillage is also a possible cause for higher K content in no-tilled plots than in the ploughed plots. Similarly, retention of crop residues can reduce losses of P, Ca, Mg and Na via soil sediments in no-tillage techniques. Chemical weeding like no-tillage increased these nutrients and CEC except for Ca, which was higher in mechanically-weeded plots than chemically-weeded plots.

Stratification of these nutrients, particularly P and K, in the surface layers of a no-tilled soil has raised concerns about their availability to plants during dry seasons. These concerns will be addressed in Chapter 7, which deals with nutrient uptake by oat under the different residue management practices. However, due to the fact that root density under no-tillage is greater in the surface soil, surface stratification of these nutrients might not have a negative effect on nutrient uptake by plants. Besides no-tillage is known to conserve soil water that can sustain modes of nutrient transport to plant roots.

No-tillage and to a certain extent mulch tillage also had a positive influence on the CEC of this Avalon soil when mouldboard ploughing served as a reference. This is in contrast to the findings of other researchers (Limousin & Tessier, 2007; Thomas *et al*., 2007; López-Fando & Pardo, 2009). According to the same authors, soil acidification following organic matter decomposition and nitrification of NH_4-based fertilizers is a major precursor for CEC decline under no-tillage as opposed to ploughing. In comparison with ploughing, Ben Moussa-Machraoui *et al*. (2010) however, observed a slightly higher CEC under no-tillage. They considered that, higher CEC in the no-tilled treatments would have been due to higher organic matter in the latter when compared to the ploughed plots. From the preceding results, none of these soil properties (soil pH and organic C) appeared to correspond with the CEC except in the upper one to two layers of no-tilled soil. Perhaps in the topsoil, higher CEC under conservation tillage systems could be attributed to higher organic C and soil pH, while in the deeper soil layer it may be associated with high clay content and lack of soil mixing, which limits a homogeneous distribution of soil particles.

As mentioned by Kotzé (2004), dramatic changes in the nutrient status of this Avalon soil occurred between 1979 and 1999. Therefore the weighed means of these nutrients and CEC to depth ranges of 0-150 mm and 0-250 mm were calculated (Table 5.13) to evaluate whether magnitude and direction of the changes observed by Kotzé (2004) still exist 10 years later. The two depth ranges were chosen because in this trial, wheat straw ashes and unburned wheat straw were incorporated through ripping and ploughing to 150 and 250 mm respectively, except in no-tilled plots. Besides that, such ranges correspond with depths of soil sampling for fertilizer recommendations (Kotzé, 2004).

As can be seen in Table 5.13, soil samples taken within the trial contained higher P, K and Mg when compared to those collected from the headlands with perennial grass outside the trial. The opposite was observed with Ca, Na and CEC, probably due to higher organic matter content that occurred in the headlands (Table 2.2). Kotzé (2004) ascribed the higher P content within the trial to the application of P fertilizer, while other nutrients were attributed to re-deposition from the deeper soil layers, and this might be the case even in this study. As displayed in Table 5.13, the values of P, K and Na decreased in the headlands and in the trial when compared to the values obtained in 1999, while Mg showed a slight decrease only in the headlands.

Table 5.13 Weighted mean macronutrient contents (mg kg^{-1}) and CEC (cmol$_c$ kg^{-1}) to 150 mm and 250 mm soil depths in the headlands with perennial grass outside the trial, and inside the trial cropped annually with wheat

Nutrient and CEC	**0-150**				**0-250**			
	Headlands		**Trial**		**Headlands**		**Trial**	
Year	1999	2010	1999	2010	1999	2010	1999	2010
P	11	8	31	24	10	7	31	22
K	336	231	362	279	216	206	327	243
Ca	894	1034	620	1027	830	1075	661	985
Mg	157	153	84	113	178	150	83	112
Na	101	58	18	17	93	69	18	18
CEC	-	7	-	6	-	7	-	6

5.3 Conclusion

Burned wheat straw increased P, K and Mg contents as opposed to unburned wheat straw. The opposite was observed with regard to Ca and Na. The methods of straw disposal had variable effects on CEC of this Avalon soil and therefore it is difficult to conclusively indicate which method between the two was superior to the other. No-tillage increased P, K, Ca, Mg, Na and CEC to various soil depths compared to stubble mulch and mouldboard ploughing. However, accessibility of these nutrients by plants under no-tillage may be restricted particularly during drought seasons. With the exception of Ca, chemical weeding also enhanced the content of these nutrients including CEC when compared to mechanical weeding.

Different treatment combinations had variable effects on these nutrients as well as on CEC. However, the interactions of straw burning x no-tillage, straw burning x chemical weeding and no-tillage x chemical weeding, generally had a positive influence on the nutrient status and CEC of this Avalon soil.

CHAPTER 6

Effects of wheat residue management on some micronutrients in soil

6.1 Introduction

The term micronutrients refer to B, Mn, Fe, Cu, Zn, Mo and Cl (Rengel, 2007); however, the focus in this chapter will be only on cationic (Mn, Fe, Cu and Zn) micronutrients. As the prefix "micro" implies, these nutrients are required in relatively small quantities by plants compared to macronutrients. Thus high concentrations of these nutrients in the soil can be toxic to plants. However, they are as essential as all the primary and secondary nutrients. In fact, if one of these micronutrients is deficient, a plant cannot complete its production cycle (Wei *et al*., 2006).

Micronutrients in soil are affected by a number of factors such as soil pH, organic matter, moisture, parent material and plant uptake, which all play a prominent role in micronutrient dynamics. These factors can lead to either deficiency or availability of micronutrients in the soil. Micronutrient deficiencies are commonly reported in arid and semi-arid soils, which are characterized by low organic matter content and neutral to alkaline pH conditions (Wei *et al*., 2006; Van der Waals & Laker, 2008). In addition, especially in South Africa, such deficiencies are widespread in commercial crop production sectors (Van der Waals & Laker, 2008), where nutrient application simply implicates addition of N, P and K (Rengel, 2007; Van der Waals & Laker, 2008). High yields achieved through N, P and K fertilization, usually hasten plant removal of micronutrients from the soil, resulting in severe micronutrient deficits (Rengel, 2007; Wright *et al*., 2007; Van der Waals & Laker, 2008). Therefore application of crop residues can help to maintain or improve nutrient balances in the soil (Yadvinder-Singh *et al*., 2005; Rengel, 2007).

Recycling of crop residues in conservation tillage systems with subsequent accumulation of organic matter exhibit stratification of micronutrient cations in the surface horizons compared to conventional tillage (Martin-Rueda *et al*., 2007; De Santiago *et al*., 2008). Soil organic matter chelates micronutrients, and thus increases their availability to plants through reduced precipitation with phosphates (Ndiaye & Krishna, 2002) or oxides (Havlin *et al*., 1999). However, according to Ndiaye and Krishna (2002) and Wei *et al*. (2006), organic matter can act as a sink for Cu and exacerbate Cu deficiency because of its potential to strongly complex and bind Cu. Alternatively, extraction of these cations by deep rooted plants and re-deposition in the topsoil during plant-fall (Rengel, 2007; De Santiago *et al*., 2008) as well as surface acidification following organic matter decomposition (Houx III *et al*., 2011) contribute to the concentration of trace elements in the top horizons of no-tilled soil.

Lower pH levels induced by organic matter decomposition and nitrification of ammonical fertilizers in no-tillage, enhance the weathering of soil minerals and thus the release of these nutrients (Limousin & Tessier, 2007). For example, Houx III *et al*. (2011) found higher Fe contents in no-tillage compared to conventional tillage, and this response was attributed to lower pH levels observed under no-tillage. On the contrary, the same authors found that conventional tillage has a potential to enhance Mn contents in the top layers compared to no-tillage. Besides Mn, Cu and Zn that had higher concentrations under no-tillage compared to conventional and minimum tillage, Fe remained unaffected by tillage (De Santiago *et al*., 2008; López-Fando & Pardo, 2009). Wright *et al*. (2007) outlined that after five years of cropping, no tillage effects were detected on Mn irrespective of N fertilization rate, but Zn contents became more pronounced under reduced tillage compared to conventional tillage. Higher Zn in the reduced tillage was ascribed to the low downward mobility of Zn and application of P fertilizer. On a semi-arid Plinthosol intensive tillage also resulted in a depletion of Zn (Du Preez *et al*., 2001). A rapid breakdown of organic matter by tillage reduces the nutrient retention capacity of soils and renders mineralized nutrients to losses through leaching and uptake by plants (Limousin & Tessier, 2007; Martin-Rueda *et al*., 2007).

Incorporation of crop residues by tillage, particularly under anaerobic soil conditions, can improve available pools of Fe and Mn through reduction processes (Yadvinder-Singh *et al*., 2005). This can be a short-term benefit however, because low redox potential leads to a soil pH increase and subsequent precipitation of carbonates (Yadvinder-Singh *et al*., 2005). In spite of that, incorporated residues encourage intensive release of nutrients. If the amount of inputs is inadequate to compensate for nutrient losses, plants may suffer nutrient stress over the long-term. In addition, tillage intensity can also stimulate oxidation of Mn and Fe in arid and semi-arid climates due to increased soil moisture losses through evapotranspiration (Havlin *et al*., 1999). Precipitated and oxidized forms of these cations are insoluble and less available to plants.

Besides the effect of soil properties on the chemistry of micronutrient cations upon addition of crop residues, the content of these nutrients in the vegetative plant parts also plays a very significant role in soil fertility. Yadvinder-Singh *et al*. (2005) estimated that a ton of wheat can extract 42 g of Cu, 777 g of Fe, 745 g of Mn and 96 g of Zn per hectare. Therefore recycling of wheat residues, either through incorporation, surface retention or burning, can potentially improve the concentration of these cations in the soil (Yadvinder-Singh *et al*., 2005). However, the amounts of these nutrients remobilized for grain development and the proportion accumulated in the straw can provide better estimates of the fraction returned to the soil (Rengel, 2007).

Decomposition liberates nutrients tied-up in crop residues into the soil system in a plant available form. However, residue decomposition stimulates microbial activity and diversity, and as a result large proportions of these nutrients may be immobilized. Straw burning through reduction in microbial biomass (Bhupinderpal-Singh & Rengel, 2007) can increase availability of cationic micronutrients. Incomplete burning of wheat straw results in accumulation of these cations in the surface soil (Sharma & Mishra, 2001); however, depending on the intensity of fire variable results can be expected (Kotzé, 2004). In a shifting cultivation, available Fe, Mn and Zn showed a marked increase after burning as opposed to Cu (Gafur *et al*., 2004). In contrast, straw burning can result in less available forms of these cations due to the increase in soil pH. Venkatesh *et al*. (2003) indicated a decline in available Fe, Zn and Cu due to burning, whereas the total fractions of these cations as well as available Mn increased.

Plant uptake as well as sensitivity of individual nutrients to high temperatures can explain the variation of these nutrients in the soil. Furthermore, micronutrient cations are less mobile (Rengel, 2007) and therefore leach at a very slow rate from residue ashes. Their loss in the soil after burning could thus be associated more with erosion than leaching (Menzies & Gillman, 2003). Incorporation of residue ashes immediately after burning can therefore alleviate the risk of erosive losses of these cations, and thus improve their concentration in the rhizosphere.

Although burning subjects essential nutrients to erosion and leaching, it can be an important tool for the release of cationic micronutrients from crop residues, particularly in areas where chemical weeding is commonly practiced. Application of herbicides, such as glyphosate, inhibits microbial activity and diversity, and consequently the decomposition of crop residues and mineralization of these nutrients (Huber, 2010). On top of that, this herbicide is capable of strongly chelating micronutrient cations and stimulating oxidation of these nutrients in the soil (Huber, 2010). As a result, acute deficiencies of these nutrients as well as impaired crop growth and yield are likely to occur. However, the situation may be reversed with the use of other herbicides like paraquat, which showed a slight increase in the concentration of micronutrient cations compared to mechanical weeding (Du Preez *et al*., 2001; Kotzé, 2004).

Generally, micronutrient cations in soils are influenced by several factors; however, soil organic matter, parent material, pH and redox potential play a significant role in the availability of these nutrients. Therefore the aim with this chapter was to evaluate the effects of different wheat residue management practices on cationic micronutrients after 30 years and to compare where possible the current results with those obtained in 1999 and 1989.

6.2 Results and discussion

6.2.1 Extractable Cu

From the summary of analyses of variance (Table 6.1), it is obvious that the applied tillage practices had a larger effect on Cu than the methods of straw disposal or weeding. The combination between tillage and weeding methods also showed a marked effect on Cu in the lower two soil layers.

Table 6.1 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on extractable Cu at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A	*			*		
B	*	*		*		
AB						
C	*					
AC						
BC					*	*
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

As illustrated in Figure 6.1, the unburned plots had a higher Cu content than the burned plots; however, significant differences occurred only in the 0-50 and 150-250 mm soil layers. At 0-50 mm soil depth, the concentration of Cu varied from 1.22 to 1.33 mg kg^{-1} and from 1.47 to 1.61 mg kg^{-1} in the 150-250 mm soil layer. Kotzé (2004) also reported that in 1999 the Cu content of unburned plots was higher than that of the burned plots, particularly in the middle two soil layers, while Cu in the upper and lower two soil layers was almost similar between the two methods of straw disposal.

Further inspection of Figure 6.1 shows that the applied tillage systems profoundly influenced this nutrient in the 0-50, 50-100 and 150-250 mm soil layers. At the soil depths of 0-50 and 150-250 mm, the ploughed plots had the highest Cu (1.39 and 1.41 mg kg^{-1} respectively) followed by mulched plots (1.28 and 1.38 mg kg^{-1} respectively) and then the no-tilled plots (1.16 and 1.26 mg kg^{-1} respectively). However, this order is reversed in the 150-250 mm soil

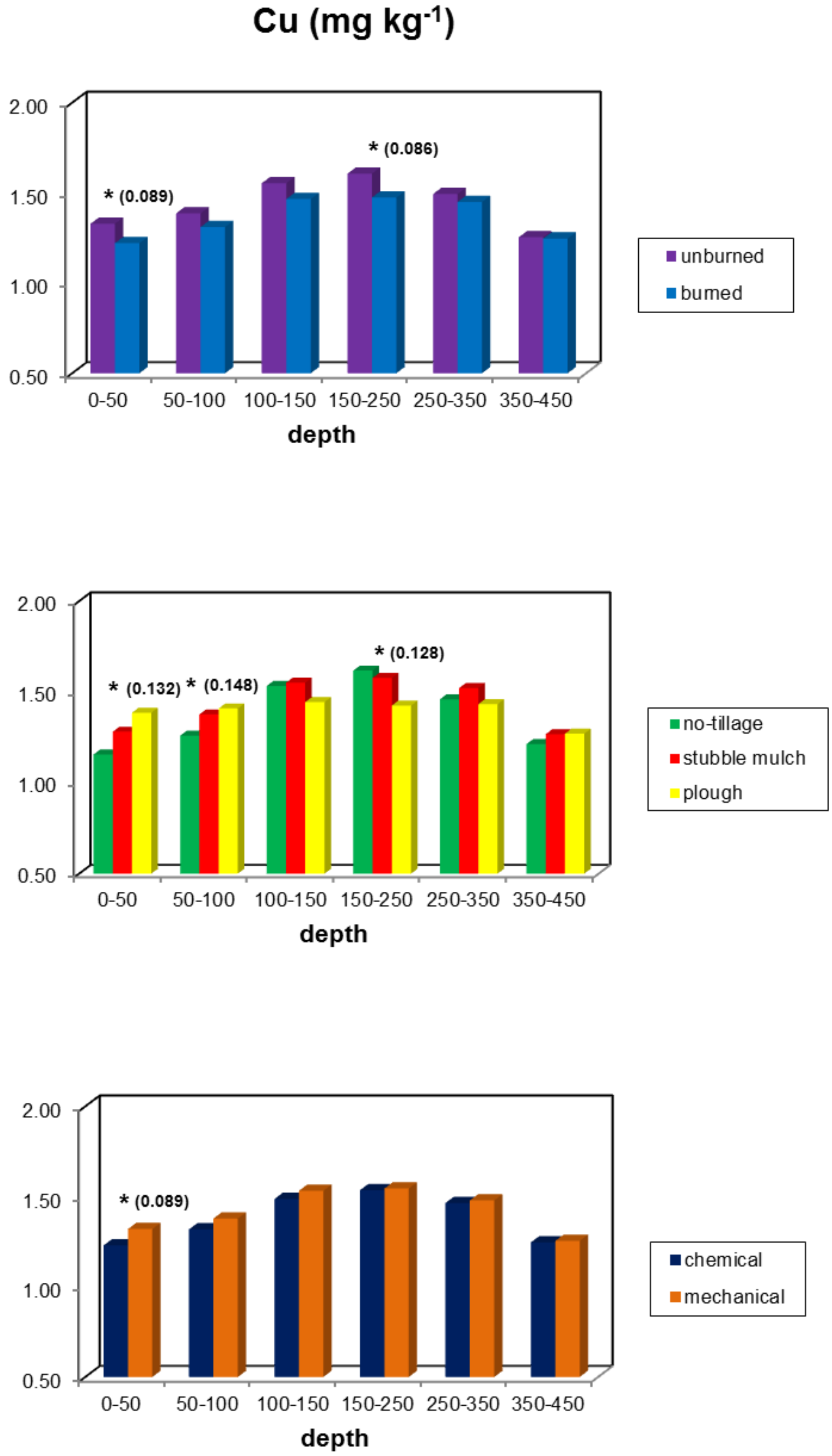

Figure 6.1 Effect of straw disposal, tillage and weed control methods on extractable Cu. LSD_T-values are shown where applicable.

interval. The mulch tillage and to some extent no-tillage also resulted in a higher Cu content than mouldboard ploughing in the 100-150 and 250-350 mm soil depths despite insignificant differences. At 350-450 mm soil depth, the mulched and ploughed plots had equal amount of Cu but higher than that of the no-tilled plots. In contrast, in 1999 different tillage systems did not show any effect on Cu throughout the sampled soil layers (Kotzé, 2004).

The weeding methods had a significant influence on extractable Cu only in the 0-50 mm soil layer (Figure 6.1). In this soil layer the Cu ranged from 1.23 mg kg^{-1} in the chemically-weeded plots to 1.32 mg kg^{-1} in mechanically-weeded plots. Although not significant, a similar pattern was observed below 50 mm soil depth. These results are not in agreement with the results obtained in 1999 (Kotzé, 2004). According to Kotzé (2004), higher Cu was conceded in the plots that were subject to chemical weeding as opposed to those that were mechanically weeded. The reasons for this variation are not known, but organic matter could be one of them. In 1999 soil organic matter was generally higher in the chemically-weeded plots than mechanically-weeded plots, which was not the case in the present study.

Interactions

Data on the effects of interactions between different treatments on Cu are presented in Table 6.2. As can be witnessed in the summary of analyses of variance (Table 6.1), Cu was markedly affected by the combination between tillage and weeding methods in the 250-350 and 350-450 mm soil depths, with LSD_T values of 0.19 and 0.23 mg kg^{-1} respectively. In the 250-350 mm soil layer no-tillage increased Cu (1.53 mg kg^{-1}) more than mouldboard ploughing (1.44 mg kg^{-1}) and stubble mulch (1.42 mg kg^{-1}) when chemical weeding was employed, whereas mulch tillage (1.62 mg kg^{-1}) resulted in a higher Cu than mouldboard ploughing (1.43 mg kg^{-1}) or no-tillage (1.39 mg kg^{-1}) when mechanical weeding was applied. At a soil depth of 350-450 mm, mechanically-weeded mulched plots contained the highest Cu content of 1.32 mg kg^{-1} and mechanically-weeded no-tilled plots had the lowest Cu content of 1.14 mg kg^{-1}. Though not significant, mechanically-weeded plots had a higher Cu content than the chemically-weeded plots in the upper three soil layers irrespective of tillage. At 150-250 mm soil depth, no-tilled and chemically-weeded plots had the greatest Cu content and the ploughed and chemically-weeded plots comprised the lowest Cu content.

There were no significant effects on Cu on account of the interactions between methods of straw disposal and tillage or methods of straw disposal and weeding methods. It is however interesting to note that compared to burning, no-burning increased Cu to a soil depth of 350 mm when no-tillage or stubble mulch was applied. Extractable Cu showed no specific trend when mouldboard ploughing was used. In the 350-450 mm soil layer, the ploughed plots that were burned had the highest Cu content, while the no-tilled plots that were burned had the

Table 6.2 Effect of the interactions between straw disposal, tillage and weed control methods on extractable Cu (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	1.28	1.33	1.38	1.29	1.37
	Burned	1.03	1.23	1.39	1.17	1.27
Weeding	Chemical	1.07	1.23	1.38		
	Mechanical	1.24	1.33	1.39		
50-100 mm layer						
Straw	Unburned	1.37	1.38	1.41	1.36	1.42
	Burned	1.15	1.37	1.41	1.28	1.34
Weeding	Chemical	1.21	1.34	1.41		
	Mechanical	1.31	1.42	1.41		
100-150 mm layer						
Straw	Unburned	1.63	1.59	1.44	1.53	1.57
	Burned	1.43	1.51	1.45	1.44	1.49
Weeding	Chemical	1.53	1.49	1.43		
	Mechanical	1.53	1.61	1.45		
150-250 mm layer						
Straw	Unburned	1.71	1.68	1.43	1.57	1.64
	Burned	1.53	1.48	1.42	1.50	1.45
Weeding	Chemical	1.66	1.53	1.42		
	Mechanical	1.58	1.63	1.43		
250-350 mm layer						
Straw	Unburned	1.52	1.54	1.42	1.48	1.50
	Burned	1.40	1.50	1.44	1.45	1.45
Weeding	Chemical	1.53	1.42	1.44		
	Mechanical	1.39	1.62	1.43		
350-450 mm layer						
Straw	Unburned	1.24	1.26	1.26	1.22	1.29
	Burned	1.18	1.27	1.29	1.28	1.22
Weeding	Chemical	1.29	1.21	1.24		
	Mechanical	1.14	1.32	1.31		

lowest Cu content. Some interesting trends were also observed between methods of straw disposal and weeding. In the upper three soil layers, mechanical weeding tended to increase Cu more than chemical weeding, regardless of the method of straw disposal. However, unburned plots contained higher Cu values than the burned plots. The trend changed below 150 mm soil depth. Except in the 350-450 mm soil interval, unburned plots had a greater Cu content than the burned plots despite the weeding method, with mechanical weeding showing higher Cu contents than chemical weeding.

In the study conducted by Kotzé (2004) a significant interaction was perceived only in the 100-150 mm soil layer between methods of straw disposal and weeding. The chemically-weeded unburned plots were found to contain the highest Cu content, whereas the chemically-weeded burned plots had the lowest Cu content. Neither significant interactions nor specific trends in Cu could be found in any other treatment combinations.

6.2.2 Extractable Fe

The summary of analyses of variance presented in Table 6.3 indicates that none of the field treatments affected extractable Fe. A significant influence was recorded only between tillage and weeding methods in the deeper two soil layers.

Table 6.3 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on extractable Fe at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A						
B						
AB						
C						
AC						
BC					*	*
ABC					*	

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Methods of straw disposal did not significantly influence Fe in any of the six soil layers (Figure 6.2). Even so, it can be seen that the burned plots contained slightly higher Fe in the

0-50, 50-100 and 150-250 mm soil layers, whereas at the soil depths of 100-150, 250-350 and 350-450 mm no-burning slightly increased this nutrient more than straw burning. After 20 years of this trial, on the contrary, unburned plots had significantly lower Fe content than the burned plots in the 0-50 mm soil depth (Kotzé, 2004). However, in the 50-100 mm soil interval no-burning slightly increased Fe more than straw burning. Below 100 mm soil depth Fe did not differ between the two straw disposal treatments.

Tillage practices also showed no significant effect on extractable Fe (Figure 6.2). Despite insignificant differences, no-tillage and stubble mulch on average resulted in an accumulation of Fe to a soil depth of 250 mm when compared to mouldboard ploughing. In the 250-350 mm soil layer, the highest Fe content was recorded in the mulched plots, followed by the ploughed plots and then the no-tilled plots. A similar trend persisted in the 350-450 mm soil depth; however, in this particular case the ploughed plots contained the highest Fe value. Kotzé (2004) also indicated that the no-tilled plots had the highest Fe content in the upper two soil layers followed by the mulched and ploughed plots, although not always significant. This trend was reversed in the bottom two soil layers. She further reported that in the middle two soil layers mulch tillage tended to increase Fe more than the other two tillage systems.

Similarly, the effect of weeding methods on Fe was not significant throughout the studied soil profile (Figure 6.2). It is however interesting to note that mechanical weeding tended to increase Fe more than chemical weeding except in the 150-250 mm soil interval. In this soil layer the chemically-weeded plots contained a slightly higher Fe than mechanically-weeded plots. Weeding methods also did not affect Fe in 1999 (Kotzé, 2004). The results revealed in this study with regard to weeding methods are in contrast to those reported by Kotzé (2004) who found that chemical weeding generally increased Fe more than mechanical weeding. In the same way as with Cu, this could be a function of soil organic matter.

Interactions

The interactive effects of different treatments on extractable Fe are summarized in Table 6.4. The summary of analyses of variance given in Table 6.3 shows that Fe was only affected significantly by the interaction between tillage and weeding methods in the soil layers of 250-350 and 350-450 mm. No-tillage increased Fe more than ploughing and stubble mulch when combined with chemical weeding, whereas stubble mulch resulted in a greater Fe content than ploughing and no-tillage when combined with mechanical weeding in the 250-350 mm soil interval with an LSD_T of 20.92 mg kg^{-1}. A similar pattern occurred in the 100-150 mm soil layer even though the difference was negligible. This nutrient showed a similar behaviour in the 350-450 mm soil layer (LSD_T = 8.13 mg kg^{-1}), though ploughing instead of stubble mulch

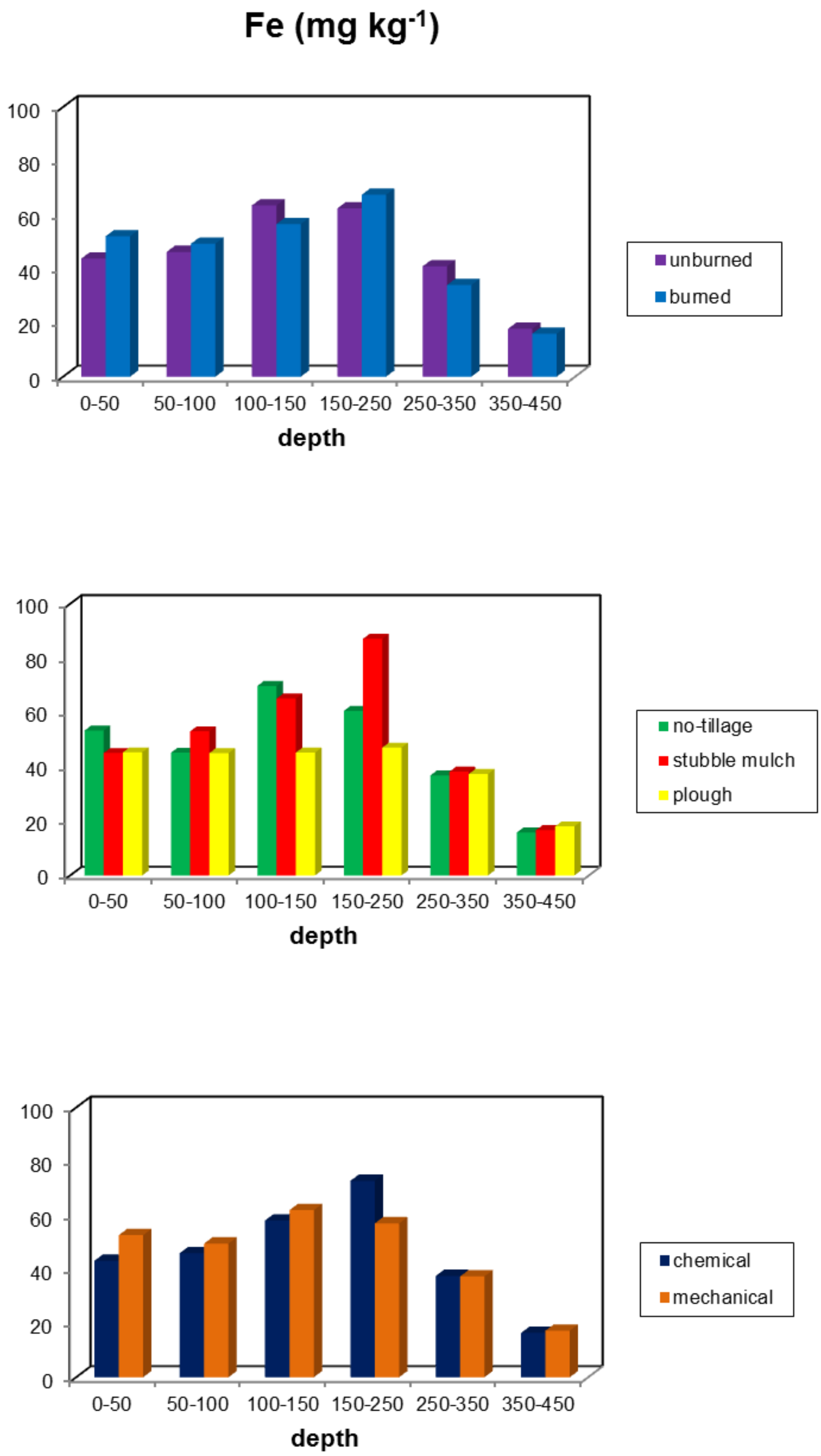

Figure 6.2 Effect of straw disposal, tillage and weed control methods on extractable Fe. LSD_T-values are shown wh0ere applicable.

had the highest Fe content when mechanical weeding was applied. The plots that were subjected to chemical weeding had a higher Fe content than those exposed to mechanical weeding in the 150-250 mm soil layer regardless of tillage; however, the mulched plots had the highest Fe content followed by no-tilled plots and then the ploughed plots.

The combination between tillage and methods of straw disposal not only showed insignificant, but also inconsistent effects on Fe in all the sampled soil layers. The interactive use of the methods of straw disposal and weeding also did not influence Fe.

Conversely, Kotzé (2004) observed a significant interaction in the upper soil layer where the mulched and unburned treatments had the highest Fe content while the mulched and burned plots had the lowest Fe content. It was also reported that no-burning increased Fe slightly more than straw burning despite the tillage or weeding method used. She further highlighted that no-tillage and stubble mulch when combined with chemical weeding rather than mechanical weeding tended to increase Fe.

Table 6.4 Effect of the interactions between straw disposal, tillage and weed control methods on extractable Fe (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	46.53	41.72	43.11	43.35	44.22
	Burned	60.20	48.49	47.55	43.02	61.15
Weeding	Chemical	35.48	42.42	51.66		
	Mechanical	71.26	47.79	39.00		
50-100 mm layer						
Straw	Unburned	51.58	43.96	43.24	46.12	46.40
	Burned	38.84	62.23	46.91	45.90	52.75
Weeding	Chemical	42.05	46.78	49.20		
	Mechanical	48.37	59.41	40.95		
100-150 mm layer						
Straw	Unburned	85.40	60.99	44.12	64.77	62.23
	Burned	54.17	69.28	46.36	51.50	61.71
Weeding	Chemical	73.82	54.38	46.20		
	Mechanical	65.75	75.88	44.28		
150-250 mm layer						
Straw	Unburned	71.69	70.82	44.74	61.65	63.18
	Burned	49.54	103.49	49.40	84.01	50.94
Weeding	Chemical	71.53	95.92	51.05		
	Mechanical	49.70	78.39	43.10		
250-350 mm layer						
Straw	Unburned	44.97	42.29	35.53	41.32	40.54
	Burned	28.67	34.20	39.17	33.79	34.24
Weeding	Chemical	46.60	31.73	34.34		
	Mechanical	27.04	44.76	40.36		
350-450 mm layer						
Straw	Unburned	18.06	18.17	17.05	17.03	18.49
	Burned	13.58	15.19	19.10	15.87	16.05
Weeding	Chemical	18.32	14.65	16.38		
	Mechanical	13.32	18.71	19.78		

6.2.3 Extractable Mn

The summary of analyses of variance indicating the significant influence of different treatments on Mn is given in Table 6.5. Inspection of Table 6.5 shows that Mn was influenced by methods of straw disposal and tillage but not by weeding methods or the interactions between the applied treatments.

Table 6.5 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on extractable Mn at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A					*	
B						*
AB						
C						
AC						
BC						
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Across all the sampled soil layers, Mn content in the burned plots was higher than that in the unburned plots though a significant difference was observed only in the 250-350 mm soil interval (Figure 6.3). At this soil interval, Mn was 13.30 mg kg^{-1} in the unburned plots and 16.78 mg kg^{-1} in the burned plots. Except in the 50-100 mm soil layer, Kotzé (2004) also found higher Mn values in the burned plots compared to the unburned plots. Nevertheless, in her study the two methods of straw disposal significantly influenced Mn in the upper and bottom soil layers.

Different tillage practices showed a significant influence on Mn only in the 350-450 mm soil layer (Figure 6.3). The ploughed plots had a higher Mn content (9.75 mg kg^{-1}) than the no-tilled plots (7.64 mg kg^{-1}), which subsequently contained a greater amount of Mn than the mulched plots (6.99 mg kg^{-1}). A similar pattern was recorded in the 250-350 mm soil interval though not significant. No consistency or significant effect could be found in the other soil depths. These observations are to a certain extent similar to those recorded after 20 years of

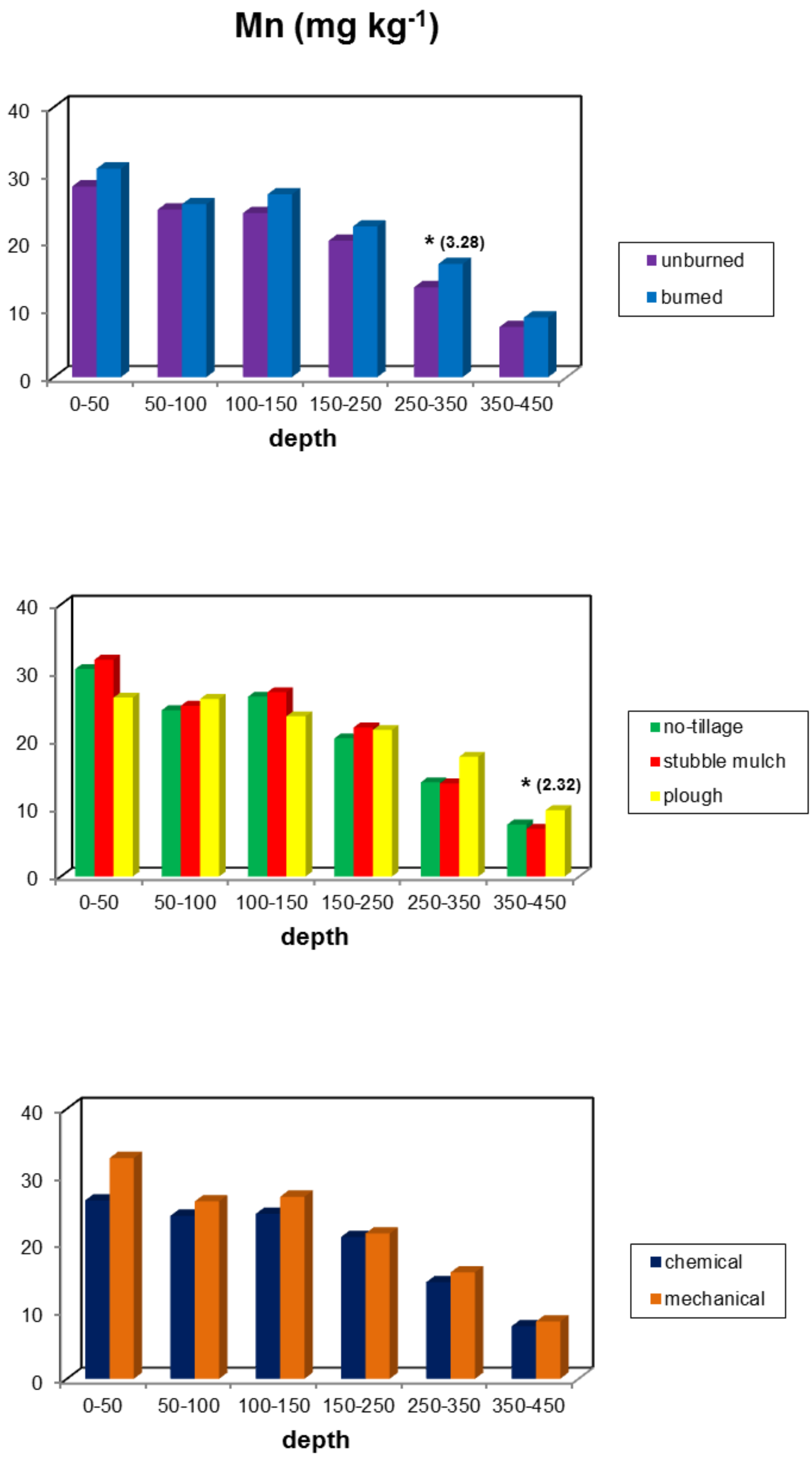

Figure 6.3 Effect of straw disposal, tillage and weed control methods on extractable Mn. LSD_T-values are shown where applicable.

this trial in spite of the fact that significant effects were considered even in the 100-150 and 250-350 mm soil depths (Kotzé, 2004).

Although no significant effect, the weeding methods had an invariable influence on Mn in all the six soil layers (Figure 6.3). The treatment plots that were subject to mechanical weeding had a slightly higher Mn content than the chemically-weeded plots. Kotzé (2004) also indicated that the weeding methods did not affect Mn. However, the findings of the present study contradict the results recorded in 1999 (Kotzé, 2004). At that stage, higher Mn contents were perceived under chemical weeding rather than mechanical weeding.

Interactions

Data on the effects of different treatment combinations on extractable Mn are presented in Table 6.6. As can be noticed in the summary of analyses of variance (Table 6.5), none of the treatment interactions produced any significant effect on Mn throughout the six soil layers. Even so, it is worthwhile to mention that in the upper four soil layers (to 250 mm soil depth), no-tilled plots contained higher Mn than either the mulched or ploughed plots when wheat straw was not burned.

Some trends also evolved between weeding and straw disposal or weeding and tillage. Across all the six soil layers, mechanical weeding resulted in a higher Mn concentration when compared to chemical weeding irrespective of the method of straw disposal. Higher Mn contents were conceded in the burned plots. A further inspection of Table 6.6 indicates that mechanically-weeded plots contained higher Mn than the chemically-weeded plots in the upper three soil layers in spite of tillage system. As indicated by Kotzé (2004), the treatment combinations did not show any significant effects or some interesting trends.

Table 6.6 Effect of the interactions between straw disposal, tillage and weed control methods on extractable Mn (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	33.57	28,79	22.37	25.18	31.30
	Burned	27.46	34.98	30.24	27.68	34.10
Weeding	Chemical	26.00	27.76	25.54		
	Mechanical	35.02	36.01	27.08		
50-100 mm layer						
Straw	Unburned	26.31	23.85	24.29	24.38	25.25
	Burned	22.57	26.38	27.93	23.92	27.33
Weeding	Chemical	20.99	24.37	27.10		
	Mechanical	27.88	25.86	25.12		
100-150 mm layer						
Straw	Unburned	28.16	23.89	20.91	22.92	25.71
	Burned	24.73	30.30	26.20	25.92	28.23
Weeding	Chemical	24.57	25.44	23.26		
	Mechanical	28.32	28.74	23.85		
150-250 mm layer						
Straw	Unburned	21.81	20.13	18.64	19.78	20.60
	Burned	18.82	23.72	24.43	22.22	22.42
Weeding	Chemical	22.00	18.88	22.12		
	Mechanical	18.63	24.96	20.95		
250-350 mm layer						
Straw	Unburned	12.74	12.68	14.49	12.79	13.82
	Burned	14.93	14.69	20.72	15.84	17.72
Weeding	Chemical	14.45	11.93	16.57		
	Mechanical	13.23	15.44	18.64		
350-450 mm layer						
Straw	Unburned	7.69	6.09	8.50	7.25	7.61
	Burned	7.58	7.89	11.00	8.29	9.35
Weeding	Chemical	8.18	6.47	8.66		
	Mechanical	7.09	7.51	10.84		

6.2.4 Extractable Zn

As displayed in the summary of analyses of variance (Table 6.7), Zn was affected by tillage and to a lesser extent by weeding methods. Neither methods of straw disposal nor any of the combinations between the employed field treatments had a significant effect on Zn.

Table 6.7 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on extractable Zn at a 95% confidence level

	Layer (mm)					
Treatments[a]	**0-50**	**50-100**	**100-150**	**150-250**	**250-350**	**350-450**
A						
B	*	*	*			
AB						
C						*
AC						
BC						
ABC						

[a]A: straw disposal, B: tillage, C: weeding

Main effects

The effect of the methods of straw disposal on extractable Zn was more or less similar to Mn despite insignificant differences for Zn (Figure 6.4). With the exception of 250-350 mm soil layer, straw burning resulted in slightly higher Zn than no-burning. Du Preez *et al*. (2001) clearly indicated that straw burning increased Zn more than no-burning throughout the studied soil layers. Kotzé (2004) found that Zn did not differ between the two methods of straw disposal in the upper and lower two soil layers. In the middle soil depths, she indicated that the burned plots had significantly higher Zn content than the unburned plots.

As illustrated in Figure 6.4, stubble mulch and no-tillage increased extractable Zn to a soil depth of 250 mm when mouldboard ploughing served as a reference; however, significant differences between these tillage methods were recorded in the upper three soil layers. The concentration of Zn in the 0-50, 50-100 and 100-150 mm soil depths was respectively 1.31, 1.35 and 1.46 mg kg^{-1} under mouldboard ploughing, 1.78, 1.76 and 1.96 mg kg^{-1} under no-tillage and 1.84, 1.78 and 1.98 mg kg^{-1} under mulch tillage. Below 250 mm soil depth, though not significant, the ploughed plots contained the highest Zn content followed by the

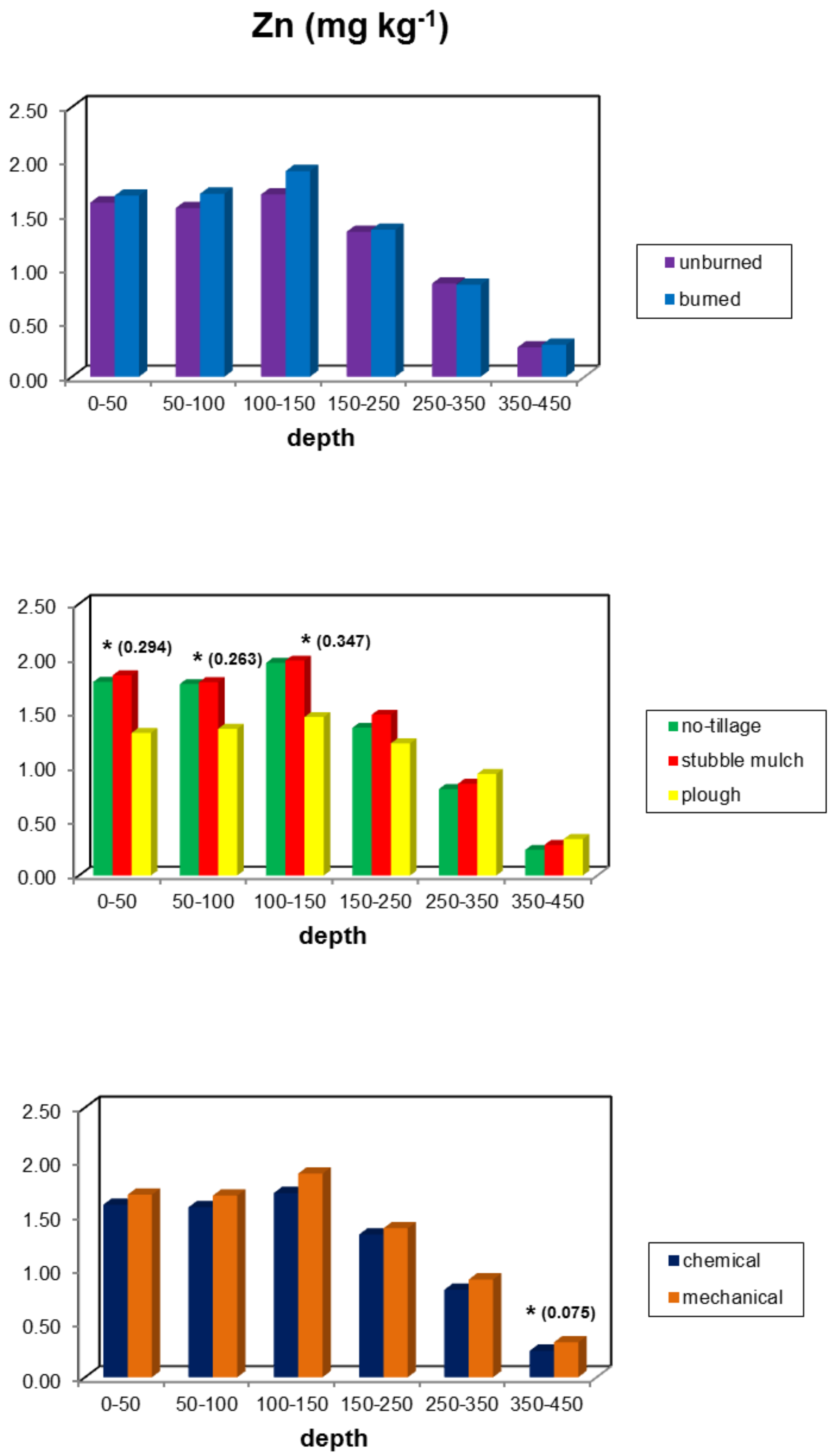

Figure 6.4 Effect of straw disposal, tillage and weed control methods on extractable Zn. LSD_T-values are shown where applicable.

mulched plots and then the no-tilled plots. In 1989/1990 no-tillage and stubble mulch also enhanced Zn in all the considered soil layers more than ploughing (Du Preez *et al*., 2001). Similar observations were reported by Kotzé (2004) who found a greater Zn content in the mulched and no-tilled plots compared to the ploughed plots particularly in the upper two soil intervals.

A further inspection of Figure 6.4 indicates that mechanical weeding resulted in an accumulation of Zn when compared to chemical weeding; however, extractable Zn differed significantly between the weeding methods in the 350-450 mm soil interval. At this soil depth the concentration of Zn ranged from 0.24 mg kg^{-1} in the chemically-weeded plots to 0.32 mg kg^{-1} in mechanically-weeded plots. In contrast, Du Preez *et al*. (2001) and Kotzé (2004) showed slightly higher Zn in the chemically-weeded plots relative to mechanically-weeded plots.

Interactions

Data on the influence of different treatment combinations on extractable Zn are given in Table 6.8. As displayed in the summary of analyses of variance (Table 6.7) neither significant interaction could be found nor some interesting trends that are worth noting.

Although Kotzé (2004) also found no significant interactions between treatment combinations, higher Zn contents were measured in the burned plots rather than unburned plots regardless of the tillage method. However, Du Preez *et al*. (2001) reported that the combination between tillage and methods of straw disposal had a significant effect on Zn. In the 0-50 mm soil depth, the burned plots that were not tilled, mulched or chemically weeded contained higher Zn contents than when ploughed or mechanically weeded. They also found that straw burning continued to improve Zn more than no-burning in the 50-150 mm soil interval in spite of tillage or weeding method. On the contrary, Zn declined with the increase in tillage intensity in the upper two soil layers of the burned, unburned and chemically-weeded plots. The concentration of Zn was the same between the no-tilled and mulched plots but higher compared to that of the ploughed plots when mechanical weeding was applied.

Table 6.8 Effect of the interactions between straw disposal, tillage and weed control methods on extractable Zn (mg kg^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
0-50 mm layer						
Straw	Unburned	1.79	1.83	1.22	1.48	1.75
	Burned	1.77	1.86	1.40	1.72	1.63
Weeding	Chemical	1.75	1.74	1.31		
	Mechanical	1.82	1.95	1.31		
50-100 mm layer						
Straw	Unburned	1.66	1.74	1.29	1.42	1.71
	Burned	1.86	1.82	1.41	1.73	1.66
Weeding	Chemical	1.75	1.68	1.30		
	Mechanical	1.77	1.88	1.40		
100-150 mm layer						
Straw	Unburned	1.75	2.04	1.28	1.52	1.86
	Burned	2.16	1.91	1.64	1.89	1.92
Weeding	Chemical	1.87	1.80	1.46		
	Mechanical	2.05	2.16	1.46		
150-250 mm layer						
Straw	Unburned	1.34	1.51	1.19	1.24	1.45
	Burned	1.38	1.45	1.25	1.41	1.31
Weeding	Chemical	1.48	1.31	1.18		
	Mechanical	1.24	1.65	1.25		
250-350 mm layer						
Straw	Unburned	0.82	0.92	0.85	0.78	0.95
	Burned	0.77	0.77	1.02	0.84	0.87
Weeding	Chemical	0.90	0.68	0.86		
	Mechanical	0.70	1.01	1.02		
350-450 mm layer						
Straw	Unburned	0.22	0.30	0.30	0.22	0.32
	Burned	0.25	0.27	0.37	0.27	0.33
Weeding	Chemical	0.25	0.25	0.24		
	Mechanical	0.23	0.32	0.43		

Based on the current results, the methods of straw disposal affected Cu and Mn more than Fe and Zn. No-burning resulted in a greater Cu and lower Mn content than straw burning to a soil depth of 450 mm, though not always significant. Extractable Zn was not significantly influenced by any of the two straw disposal treatments; however, the burned plots had a slightly higher Zn than unburned plots throughout the soil profile. As mentioned by Gafur *et al.* (2004) burning of vegetation under shifting cultivation increased Mn, Zn and Fe but not Cu. Copper might be more sensitive to high temperatures. Sharma and Mishra (2001) reported that incomplete burning of wheat straw did not result in the losses of these micronutrient cations, but when the soil samples were subjected to different temperature regimes Cu as opposed to the other three cations decreased with an increase in temperature. Therefore differences in fire intensity can be the cause of these variations on account of Cu.

Copper also exhibited a different behaviour from the other three investigated cations when comparing the three tillage practices that have been applied for 30 years since the initiation of this trial. To a soil depth of 100 mm, the Cu content of the ploughed plots was highest followed by that of the mulched plots and then no-tilled plots. This trend changed in the next three soil layers. Although not always significant, no-tillage and stubble mulch increased Zn, and Mn, especially in the surface layers when ploughing served as a reference. As with the methods of straw disposal, tillage did not affect Fe. Lopez-Fando and Pardo (2009) also found higher Mn and Zn contents under no- and zero-tillage as opposed to minimum tillage and mouldboard ploughing. Copper and Fe were not affected by any of the tillage systems; however, they indicated that Fe increased with an increase in soil depth under mouldboard ploughing. De Santiago *et al*. (2008) showed higher contents of Mn, Cu and Zn under no-tillage compared to ploughing or minimum tillage. Tillage did not show any effect on Fe according to the same authors.

Surface stratification of Zn and Mn in no-tilled soils as opposed to cultivated soils is probably the result of re-deposition of these nutrients from the deeper soil horizons during plant fall, surface placement of inorganic fertilizers containing these cations as impurities as well as poor soil mixing (Kotzé, 2004; Martin-Rueda *et al*., 2007; Rengel, 2007; De Santiago *et al*., 2008). In addition, some researchers (Martin-Rueda *et al*., 2007; De Santiago *et al*., 2008) have shown that increased soil organic matter under no-tillage can be accountable for higher micronutrient cations in no-tillage compared to ploughing. Soil organic matter is said to reduce oxide precipitation rates and promote the solubility of these cations (especially Mn and Fe) (Rengel, 2007; De Santiago *et al*., 2008). On the other hand higher organic C can result in low Cu (Ndiaye & Krishna, 2002; Wei *et al*., 2006), and this could possibly be the reason for a lower Cu content in the upper soil layers of the no-tilled plots compared to the ploughed plots in the current study. Although this might be the case, De Santiago *et al*. (2008) have clearly indicated that the DTPA method can effectively extract these cations even when bound to soil organic matter.

In spite of the fact that weeding methods had a lesser effect on micronutrient cations than tillage, mechanical weeding consistently increased these nutrients more than chemical weeding. There might be some other factors attributable to this response; however, higher organic matter under mechanically-weeded plots as compared to those treated with herbicides could be the main cause. According to Rengel (2007) electrons generated during organic matter decomposition and microbial respiration reduce redox potential in soil, and thus increase the solubility of these cations. In general, parent materials can also contribute significantly to the concentration of these nutrients in the soil (Barnard & Du Preez, 2004) and therefore result in conflicting observations between studies.

Data on the weighted means of micronutrient cations to soil depths of 0-150 and 0-250 mm in the headlands with perennial grass outside the trial, and inside the trial cropped annually with wheat are presented in Table 6.9. The reasons for selecting these depth ranges were given in the preceding chapter.

Table 6.9 Weighted mean micronutrient contents to 150 mm and 250 mm soil depths in the headlands with perennial grass outside the trial, and inside the trial cropped annually with wheat

Nutrient mg kg^{-1}	**0-150**				**0-250**			
	Headlands		**Trial**		**Headlands**		**Trial**	
Year	1999	2010	1999	2010	1999	2010	1999	2010
Cu	3	2	5	1	3	2	6	1
Fe	46	214	58	52	34	170	45	57
Mn	47	43	63	27	36	37	56	25
Zn	3	3	5	2	3	2	6	2

As displayed in Table 6.9, soil samples collected outside the trial contained higher levels of these nutrients when compared to those taken inside the trial. This response can possibly be associated with higher organic matter (Martin-Rueda *et al*., 2007; De Santiago *et al*., 2008) and lower pH values (Houx III *et al*., 2011) found in the soil samples collected the headlands. A further inspection of Table 6.9 shows that different wheat residue management practices resulted in a decline of these cations within the last 10 years of this trial when the previous study by Kotzé (2004) served as a reference. The results of this study and the previous one by Kotzé (2004) however, justified the fact that organic matter is the “backbone” of soil fertility. Though correlations between the studied soil fertility indicators were not done, it seems that the micronutrient cations tended to increase with an increase in soil organic matter.

6.3 Conclusion

Although not always significant, burned wheat straw increased Mn and Zn but not Cu when compared to unburned wheat straw. No significant effect or specific trend could be observed with regard to Fe as a result of the methods of straw disposal. Similarly, tillage also did not show any significant influence on Fe; however, it can be noted that no-tillage and stubble mulch tended to increase Fe to 250 mm soil depth compare to mouldboard ploughing. Stubble mulch and no-tillage resulted in an accumulation of Mn and Zn, whereas mouldboard ploughing increased Cu, particularly in the top soil. Irrespective of mostly insignificant differences, mechanical weeding on average resulted in higher levels of these cations when compared to chemical weeding. Based on these results, the concentration of micronutrients in this Avalon soil seems to coincide with an increase in organic matter content.

CHAPTER 7

Effects of wheat residue management on nutrient uptake and yield

7.1 Introduction

Conservation tillage and crop residue management practices have recently gained recognition due to their potential to restore, maintain or improve soil fertility (Wright *et al*., 2007; Ben Moussa-Machraoui *et al*., 2010; Dalal *et al*., 2011). Generally, conservation tillage systems enhance soil physical, chemical and biological properties, which are essential for crop growth and yield. However, nutrient availability to plants, and hence grain yield under these management systems is still questionable due to surface stratification of plant nutrients.

Several studies have shown that accumulation of nutrients at or near the soil surface in conservation tillage as opposed to mouldboard ploughing can have negative implications on nutrient uptake and crop productivity, particularly in arid to semi-arid soils, which are characterized by low moisture content (Du Preez *et al*., 2001; Kotzé, 2004; Lupwayi *et al*., 2006b; Thomas *et al*., 2007; Deubel *et al*., 2011). Soils in the arid and semi-arid regions normally have low organic matter levels (Mills & Fey, 2003; Kotzé & Du Preez, 2007), and as a result tend to dry out quickly during drought seasons, especially in the topmost soil layer (Deubel *et al*., 2011). This can certainly hamper nutrient diffusion and/or mass flow processes which depend mainly on soil moisture.

Differences in nutrient uptake as a result of tillage and crop residue management systems may not be solely associated with surface nutrient stratification. Thus, the nature (mobile or immobile) and crop demand for individual nutrients can also have a significant influence on crop nutrient uptake. For example, Vogeler *et al*. (2009) indicated that application of NPK fertilizer combined with farm-yard manure resulted in an accumulation of available P in the topsoil, but the uptake was significantly higher for N compared to P, suggesting that crop N requirement was higher compared to that of P, or perhaps N due to its mobility moved down to the root zone and therefore became accessible to plant roots. The same authors however, indicated no significant effect of tillage on N and P uptake. Garcia *et al*. (2007) found that at six-leaf growth stage, the P uptake by the test crops was often lower under no-tillage than with mouldboard ploughing. At the stage of physiological maturity, the highest P uptake by maize was again recorded with mouldboard ploughing and chisel tillage and least under no-tillage and disk tillage. They attributed this response to enhanced P distribution and availability in the 50-200 mm soil layer as well as reduced soil densification, which might have stimulated root proliferation under mouldboard ploughing. The same authors therefore suggested that one-time tillage of no-tilled soil once in at least 10 years can be a viable measure to reduce surface stratification of nutrients, improve nutrient uptake and subsequently grain yield in conservation tillage systems.

Deubel *et al*. (2011) however, noted that one-time tillage of no-tilled soil might not be necessary because increased availability of P and K in the surface soil can promote the supply to the growing plants. Besides, nutrient stratification in the surface of a no-tilled soil as a result of continuous application of crop residues and fertilizers may lead to a nutrient equilibrium state after a couple of years (Deubel *et al*., 2011). According to the same researchers, as the storage capacity of the surface soil gets saturated, nutrients will start moving downward to curb deficiencies in the root zone. This phenomenon may hold true based on the findings of other research workers. Mozafar *et al*. (2000) reported that at most sampling dates absorption of P, Zn and Cu by maize as well as P, K, Mn and Zn by wheat was more pronounced under no-tillage than mouldboard ploughing. On the contrary, at early growth stages, Ca and Mn uptake by maize as well as Ca uptake by wheat were higher with mouldboard ploughing as opposed to no-tillage. Lupwayi *et al*. (2006b) also found that no-tillage increased N uptake by wheat with 26% when compared to mouldboard ploughing. Mouldboard ploughing and intensive burning of crop residues can reduce plant uptake of especially immobile nutrients by disrupting the root-hyphael network in the soil (Mozafar *et al*., 2000).

Some researchers on the other hand, believe that burning of crop residues also has a potential to improve nutrient absorption by crops due to rapid release of nutrients in available forms for plant use and reduced microbial nutrient immobilization rates (Du Preez *et al*., 2001; Bhupinderpal-Singh & Rengel, 2007; Rengel, 2007; Kotzé & Du Preez, 2008). Stubble burning is also likely to supply even immobile nutrients in the deeper soil horizons where root distribution and density are often high. Nutrients like K leaches quickly from crop residue ashes into the soil system (Menzies & Gillman, 2003), and as a result chances are high for subsequent crops to make use of it at early growing stages when they need it most. Crop residue burning also eradicates weeds, and pests that can cause a decline in plant biomass and grain yield. Crop residues that accumulate on the soil surface after harvesting are also reduced in the burned treatments, and therefore impedance to the newly growing crops is minimized when compared to unburned treatments (Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007).

Alternatively, Adetunji (1997) concluded that in a long-term trial, residue incorporation especially with recommended rates of NPK fertilizer, is likely to sustain nutrient uptake and grain yield more than the common practice of burning crop residues. Stubble burning can result in low plant biomass production and grain yield due to substantial losses of some essential nutrients (C, N and to some extend S) into the atmosphere (Sharma & Mishra, 2001; Heard *et al*., 2006; Rengel, 2007). Micronutrient uptake may also be restricted due to increased pH levels following stubble burning. High soil pH reduces the solubility and availability of micronutrient cations, hence their uptake by plants. Blockage of soil pores by fine ash particles as well as soil desiccation in the surface can also impede infiltration of water needed for nutrient transport to plant roots (Bhupinderpal-Singh & Rengel, 2007). Consequently, available nutrients released during and after stubble burning may be washed away by runoff water or wind.

Stubble burning, which is mostly practiced to reduce obstruction to tillage implements as well as to destroy a habitat for pests and diseases, does not seem to be effective, particularly with regard to the control of pests and diseases (Kutcher & Malhi, 2010). Therefore these authors concluded that crop residues should be managed by other means rather than fire. Kumar and Goh (2002) are of the opinion that although burned crop residues increased wheat grain yield more than unburned straw, alleviation of the problems (nutrient immobilization as well as weed, pest and disease infestation) associated with residue retention can give comparable yields.

Application of inorganic fertilizers to meet microbial nutrient requirement reduces nutrient immobilization rates, while pests and diseases can be managed by first controlling weeds, which serve as a host. Weed control methods not only destroy the habitat for pathogens and diseases, but also reduces competition for growth promoting factors (nutrients, water and light energy) between the desired crops and weeds. Even so, the commonly used weeding methods (mechanical and chemical) may have different effects on nutrient uptake by crops and ultimately biomass and grain yield. Some herbicides such as Mecoprop and MCPA (2-methyl-4-chloro phenoxy acetic acid) cause deformation of plant roots (Tottman & Davies, 1978) and that reduces their ability to absorb nutrients. Pardo *et al*. (2011) showed that application of either herbicides or mechanical weed control did not affect grain yield of the used cereals. According to Pardo *et al*. (2011) the control plots increased grain yield more than the treated plots. Qasem (2007) also reported that the soil application of isoproturon and dimethenaid supressed wheat grain yield more than weed-free treatments (hand-pulled). Hand-pulling uproots weeds and prevents regrowth; nonetheless, it may not be a feasible method or practice at commercial level.

In general, the uptake of nutrients by crops depends on soil conditions, the nature of nutrients, plant nutrient requirement and plant species. The ability to utilize absorbed nutrients ultimately influence biomass and grain yield. Information in relation to nutrient uptake by oat is limited. The initial aim with this chapter was to evaluate the long-term effects of residue management practices on (i) biomass yield and nutrient uptake of wheat in 2010 and (ii) grain yield of wheat from 1979 to 2010. In 2010 oat was planted as a substitute crop for wheat to reduce the occurrence of “Take all” in some treatments. Thus the biomass yield and nutrient uptake of oat were measured in 2010.

7.2 Results and discussion

7.2.1 Biomass yield and nutrient uptake of oat in 2010

7.2.1.1 Biomass yield

As illustrated in the summary of analyses of variance (Table 7.1), tillage and straw disposal methods significantly influenced biomass yield of oat. Weeding methods did not show any significant effect on biomass production. The interaction between tillage and straw disposal methods as well as tillage and weeding methods had a significant effect on biomass yield of oat.

Table 7.1 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on biomass yield of oat at mid-shooting stage at a 95% confidence level

Treatments[a]	**Biomass yield**
A	*
B	*
AB	*
C	
AC	
BC	*
ABC	

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Inspection of Figure 7.1 shows that a significantly higher biomass yield of oat was recorded with the burned straw than unburned straw. The average biomass yield ranged from 1.51 t ha^{-1} in unburned treatments to 1.79 t ha^{-1} in the burned treatments.

Similarly, the applied tillage methods also had a significant influence on biomass yield of oat (Figure 7.1). Biomass yield was highest (1.96 t ha^{-1}) in the ploughed plots, intermediate (1.53

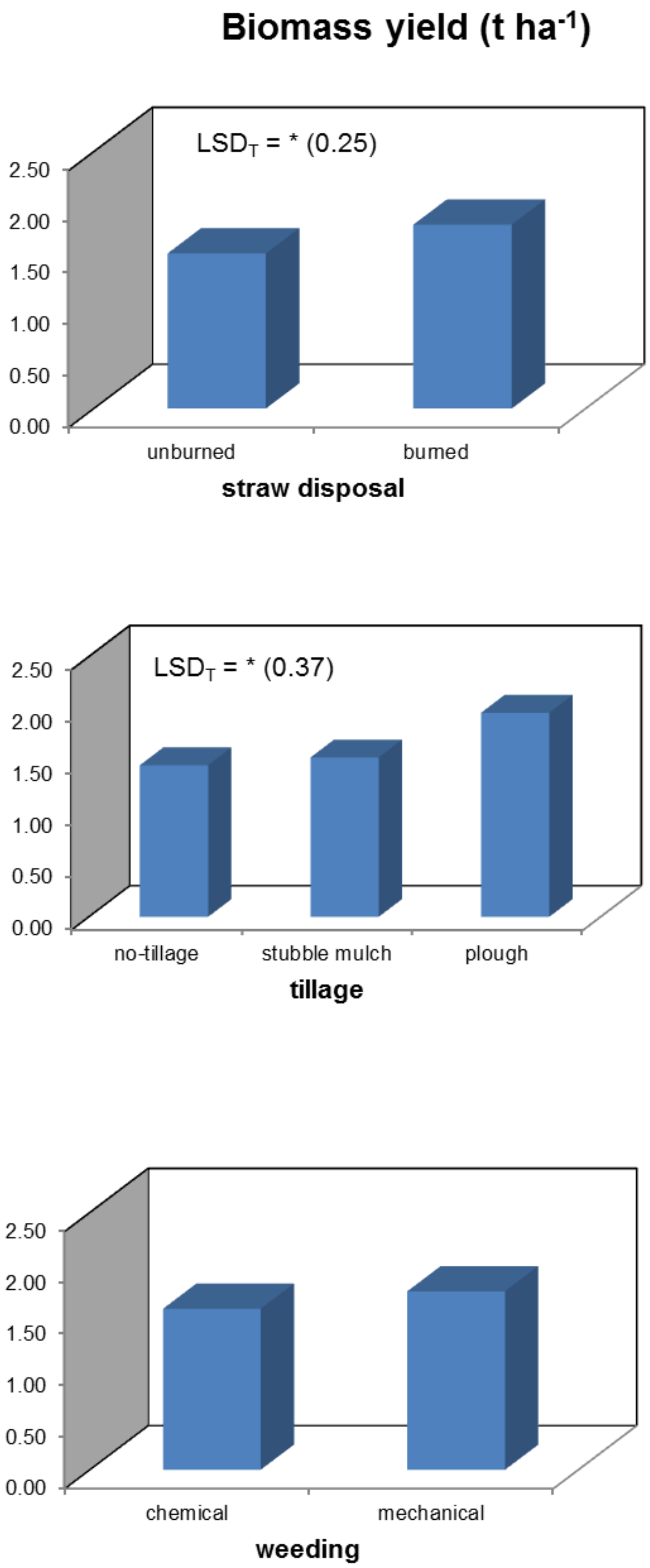

Figure 7.1 Effect of straw disposal, tillage and weed control methods on biomass yield of oat at mid-shooting stage. LSD_T-values are shown where applicable.

t ha^{-1}) in the mulched plots and lowest (1.46 t ha^{-1}) in the no-tilled plots.

As stated earlier, no significant effects could be found on biomass yield of oat as a result of weeding methods (Figure 7.1). However, it can be seen that biomass yield was slightly higher in the plots that were mechanically weeded when compared to those that were treated with herbicides.

Interactions

Data on the effects of treatment combinations on biomass yield are presented in Table 7.2. As highlighted in the summary of analyses of variance (Table 7.1), the interactions between tillage and straw disposal methods as well as tillage and weeding methods significantly affected biomass yield of oat with an LSD_T of 0.65 t ha^{-1}. In contrast to the no-tillage and mulched treatments burning of straw in the ploughed plots resulted in a higher biomass yield when compared to no-burning. In no-tilled plots, mechanical weeding in significantly higher oat biomass when compared to chemical weeding. No significant differences in oat biomass due to weeding were recorded in the mulched and ploughed plots. The combination between methods of straw disposal and weeding did not cause any significant effect on plant biomass.

Table 7.2 Effect of the interactions between straw disposal, tillage and weed control methods on biomass yield of oat at mid-shooting stage (t ha^{-1})

		Tillage			**Weeding**	
		None	Mulched	Ploughed	Chemical	Mechanical
Straw	Unburned	1.41	1.16	1.95	1.40	1.62
	Burned	1.50	1.90	1.97	1.73	1.85
Weeding	Chemical	1.11	1.50	2.08		
	Mechanical	1.80	1.56	1.84		

7.2.1.2 Nutrient content

The summary of analyses of variance (Table 7.3) indicates that methods of straw disposal, tillage and weeding significantly affected the content of some nutrients in oat straw. A significant interaction was observed between tillage and weeding only on Cu content.

Table 7.3 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on nutrient content of oat at mid-shooting stage at a 95% confidence level

	Nutrient content										
Treatments[a]	**N**	**P**	**K**	**S**	**Ca**	**Mg**	**Na**	**Cu**	**Fe**	**Mn**	**Zn**
A						*	*	*			*
B					*			*			
AB											
C		*			*		*	*			
AC											
BC								*			
ABC											

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Methods of straw disposal had a significant effect on the concentration of Mg (Figure 7.2) as well as Na, Cu and Zn (Figure 7.3) in oat straw. The concentration of Mg, Na, Cu and Zn ranged from 0.14%, 355.74 mg kg^{-1}, 4.44mg kg^{-1} and 15.37mg kg^{-1}, respectively in oat planted in unburned plots to 0.15%, 488.43mg kg^{-1}, 5.25mg kg^{-1} and 16.83mg kg^{-1}, respectively in oat grown in the burned plots. The N, P, K, S and Ca (Figure 7.2) as well as Fe and Mn (Figure 7.3) contents were not significantly affected by the applied methods of straw disposal; however, no-burning resulted in higher N, K and Fe content when compared to straw burning. In contrast, S and Mn concentration in oat straw was slightly greater in the burned plots than in unburned plots. On average, oat had 0.19% P and 0.15% Ca despite the method of straw disposal.

Tillage practices had a significant effect only on Ca (Figure 7.2) and Cu (Figure 7.3) content of oat. The Ca content was highest in oat (0.16%) grown in no-tilled plots, followed by oat (0.14%) in the ploughed plots and then oat (0.13%) in the mulched plots. The trend was reversed with Cu. Plant Cu was highest (5.56 mg kg^{-1}) with stubble mulch, intermediate (4.93 mg kg^{-1}) under mouldboard ploughing and lowest (4.06 mg kg^{-1}) in no-tillage system. There were no significant differences between the applied tillage systems on N, P, K, S and Mg (Figure 7.2) as well as Na, Fe, Mn and Zn (Figure 7.3) content of oat. However, it can be pointed out that mouldboard ploughing tended to increase the concentration of N, K, S and Na in oat when compared to no-tillage or stubble mulch. Oat in no-tilled plots, on the

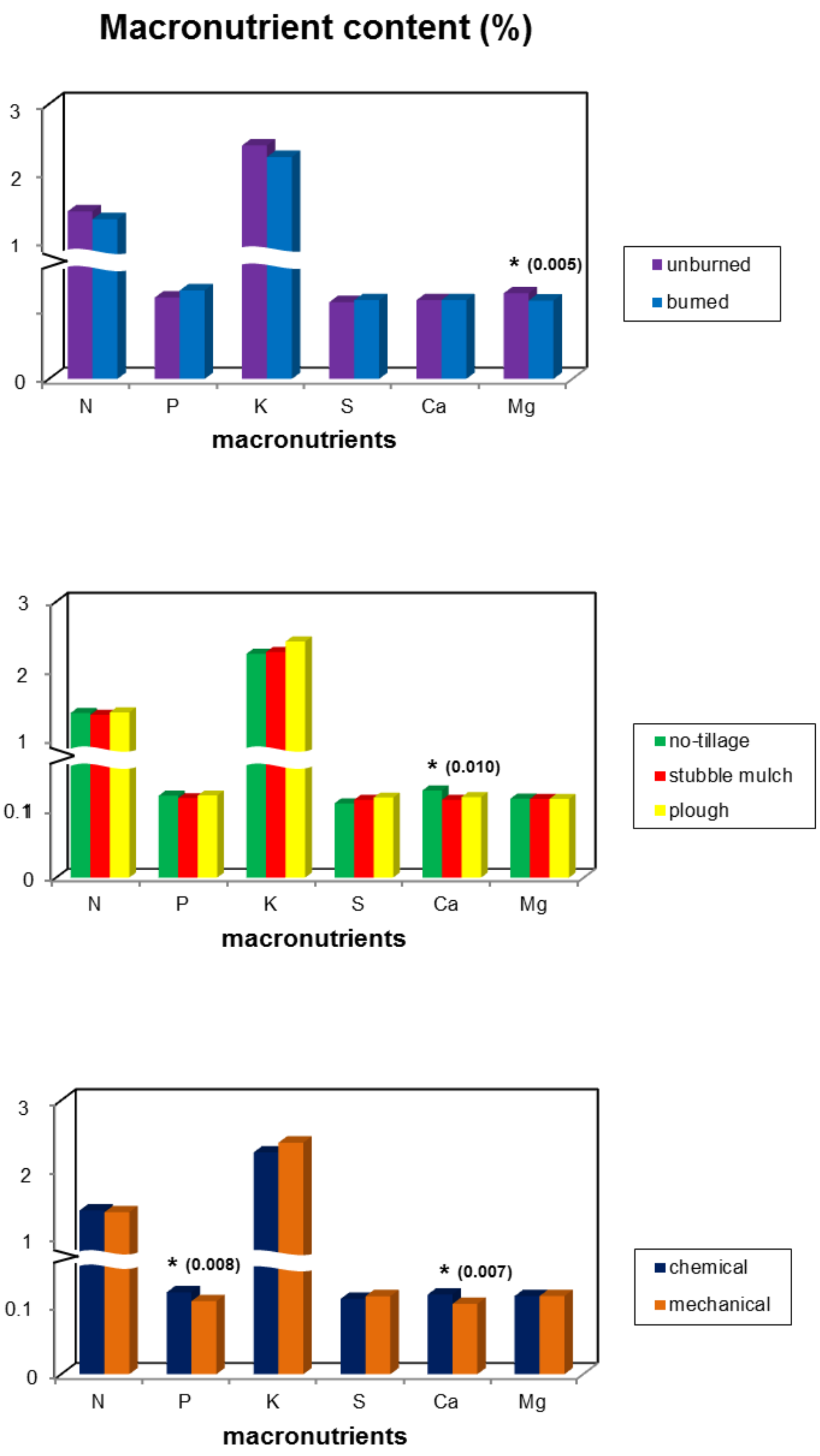

Figure 7.2 Effect of straw disposal, tillage and weed control methods on macronutrient content of oat at mid-shooting stage. LSD_T-values are shown where applicable.

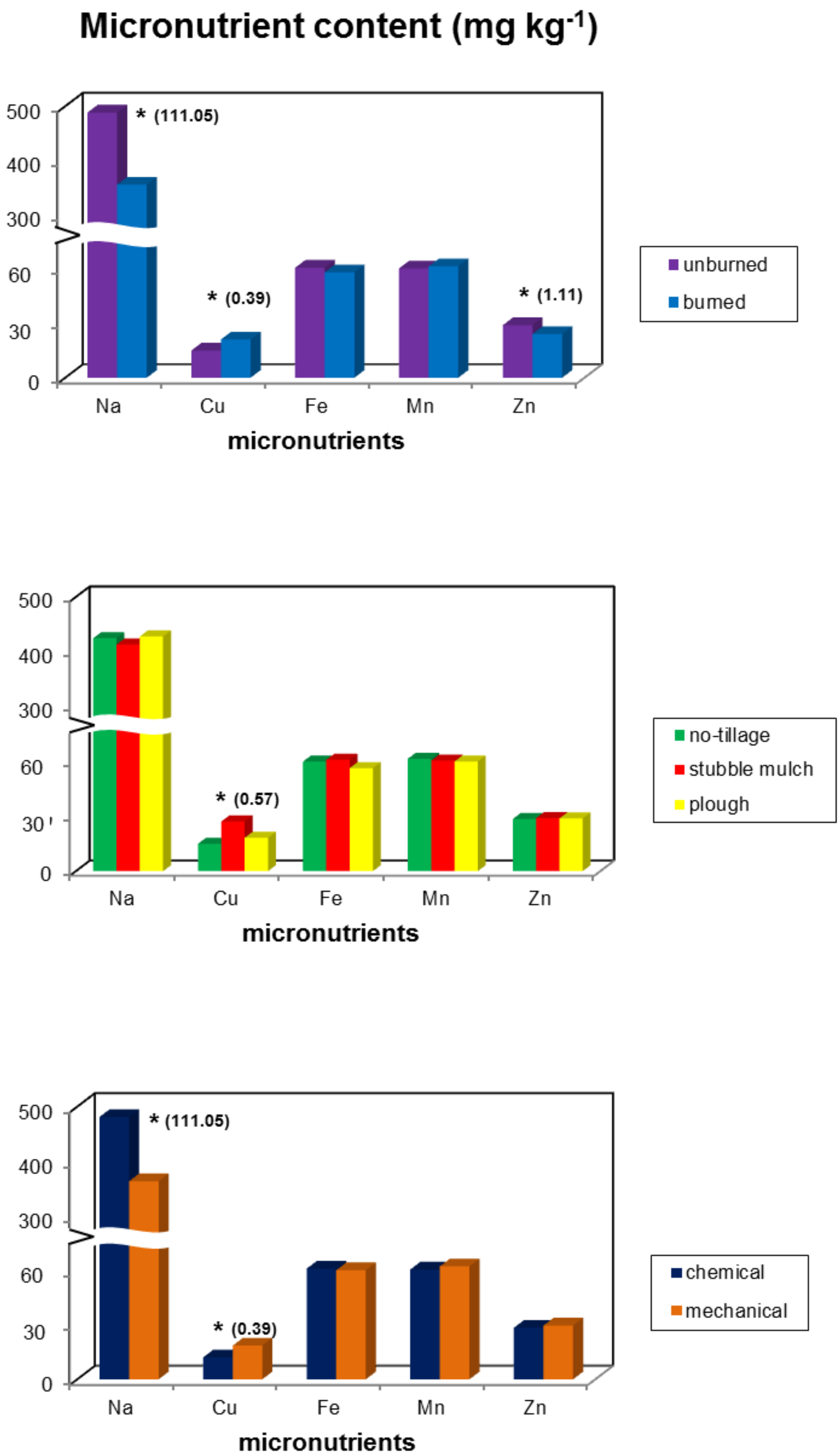

Figure 7.3 Effect of straw disposal, tillage and weed control methods on micronutrient content of oat at mid-shooting stage. LSD_T-values are shown where applicable.

contrary, had slightly higher P, Mg and Mn content when compared to oat planted in mulched or ploughed plots, while Fe and Zn content was greater in the mulched plots than in the ploughed or no-tilled plots.

The weeding methods showed a significant influence on P and Ca (Figure 7.2) as well as Na and Cu (Figure 7.3) content. Chemical weeding increased P, Ca and Na content in oat significantly more than mechanical weeding. The P, Ca and Na content ranged from 0.18%, 0.13% and 363.15 mg kg^{-1}, respectively to 0.20%, 0.17% and 481.02 mg kg^{-1}, respectively. The pattern changed with plant Cu, with Cu content being highest (5.63 mg kg^{-1}) under mechanical weeding and lowest (4.06 mg kg^{-1}) under chemical weeding. Though insignificant, mechanical weeding resulted in a higher content of K and S (Figure 7.2) as well as Mn and Zn (Figure 7.3) and lower N (Figure 7.2) and Fe (Figure 7.3) content when compared to chemical weeding. Magnesium concentration in oat was 0.14% regardless of the weeding method.

Interactions

Data on interactions between field treatments on nutrient content of oat are illustrated in Table 7.4. As indicated in the summary of analyses (Table 7.3), the only significant interaction was recorded between tillage and weeding methods on Cu with an LSD_T of 1.00 mg kg^{-1}. Compared to chemical weeding, mechanical weeding combined with any of the applied tillage practices enhanced the concentration of Cu in oat. However, the highest Cu content (6.72 mg kg^{-1}) was recorded in oat planted in mechanically-weeded mulched plots, followed by plants grown (5.64 mg kg^{-1}) in mechanically-weeded ploughed plots and then those (4.53 mg kg^{-1}) in mechanically-weeded no-tilled plots. No significant interactions were found with regard to the concentrations of other nutrients in oat.

Table 7.4 Effect of the interactions between straw disposal, tillage and weed control methods on nutrient content of oat at mid-shooting stage

	N (%)					**P (%)**					**K (%)**				
	Tillage			**Weeding**		**Tillage**			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	1.50	1.38	1.44	1.45	1.43	0.19	0.18	0.19	0.20	0.18	2.41	2.27	2.51	2.26	2.54
Burned	1.28	1.34	1.35	1.34	1.31	0.19	0.19	0.19	0.20	0.18	2.08	2.27	2.33	2.22	2.23
Weeding Chemical	1.37	1.34	1.47			0.20	0.19	0.20			2.12	2.17	2.43		
Mechanical	1.40	1.38	1.32			0.18	0.17	0.18			2.37	2.37	2.41		

	S (%)					**Ca (%)**					**Mg (%)**				
	Tillage			**Weeding**		**Tillage**			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	0.08	0.13	0.14	0.11	0.12	0.16	0.13	0.15	0.16	0.13	0.15	0.15	0.14	0.14	0.15
Burned	0.07	0.12	0.18	0.09	0.16	0.16	0.13	0.15	0.17	0.13	0.14	0.14	0.14	0.14	0.14
Weeding Chemical	0.10	0.10	0.11			0.18	0.14	0.17			0.14	0.14	0.14		
Mechanical	0.06	0.16	0.21			0.15	0.11	0.12			0.15	0.14	0.14		

	Na (mg kg^{-1})					**Cu (mg kg^{-1})**					**Fe (mg kg^{-1})**				
	Tillage			**Weeding**		**Tillage**			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	458.06	486.67	520.56	590.56	386.30	4.25	5.97	5.53	4.35	6.15	62.25	62.56	63.17	61.11	64.20
Burned	391.67	340.00	335.56	371.48	340.00	3.86	5.14	4.33	3.78	5.11	57.81	63.64	52.92	60.22	56.02
Weeding Chemical	445.00	473.33	524.72			3.58	4.39	4.22			62.92	62.72	56.36		
Mechanical	404.72	353.33	331.39			4.53	6.72	5.64			52.14	63.47	59.72		

	Mn (mg kg^{-1})					**Zn (mg kg^{-1})**				
	Tillage			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	69.50	58.14	56.50	57.78	64.98	16.33	17.17	17.00	15.98	17.69
Burned	60.64	64.86	63.81	64.87	61.33	14.19	16.25	15.67	15.13	15.61
Weeding Chemical	66.53	63.42	54.03			14.83	16.17	15.67		
Mechanical	63.61	59.58	66.28			15.69	17.25	17.00		

7.2.1.3 Nutrient uptake

As displayed in the summary of analyses of variance (Table 7.5), the applied tillage practices influenced nutrient uptake more than either straw disposal or weeding methods. Tillage systems combined with either methods of straw disposal or weeding also significantly affected the uptake of some nutrients.

Table 7.5 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on nutrient uptake by oat at mid-shooting stage at a 95% confidence level

	Nutrient content										
Treatments[a]	**N**	**P**	**K**	**S**	**Ca**	**Mg**	**Na**	**Cu**	**Fe**	**Mn**	**Zn**
A		*									
B	*	*	*	*	*	*		*			*
AB		*						*	*		
C								*			
AC											
BC	*	*			*	*					
ABC											

[a]A: straw disposal, B: tillage, C: weeding

Main effects

Straw disposal methods only significantly influenced the uptake of P by oat (Figure 7.4). This P uptake by oat ranged from 2.83 kg ha^{-1} in unburned treatments to 3.37 kg ha^{-1} in the burned plots. Despite insignificant differences, N, K, S, Ca and Mg uptake (Figure 7.4) as well as Cu, Fe, Mn and Zn uptake (Figure 7.5) were higher in the burned plots rather than in unburned plots. In contrast, Na uptake was slightly higher in unburned plots than in the burned plots.

The applied tillage methods had a significant effect on the uptake of N, P, K, S, Ca and Mg (Figure 7.4) as well as that of Cu and Zn (Figure 7.5). The uptake of these nutrients was highest in the ploughed plots, intermediate in the mulched plots and lowest in no-tilled plots. A similar trend was observed with Fe and Mn uptake, though not significant. The Ca uptake was also highest (2.93 kg ha^{-1}) with mouldboard ploughing, but lowest (1.97 kg ha^{-1}) in stubble mulch while intermediate (2.33 kg ha^{-1}) under no-tillage. Though insignificant, Na uptake was higher in the ploughed plots than in the mulched or no-tilled plots.

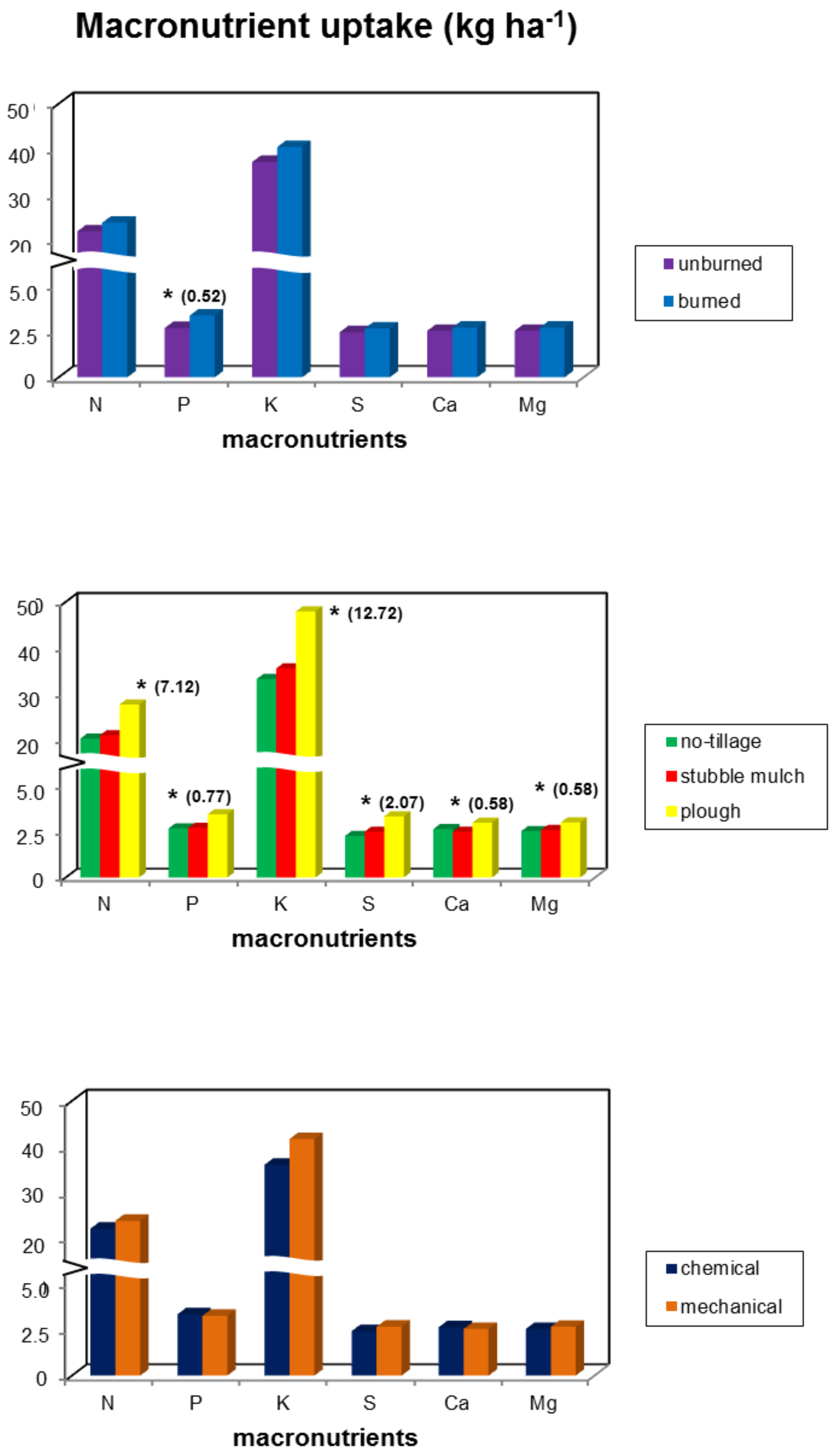

Figure 7.4 Effect of straw disposal, tillage and weed control methods on macronutrient uptake by oat at mid-shooting stage. LSD_T-values are shown where applicable.

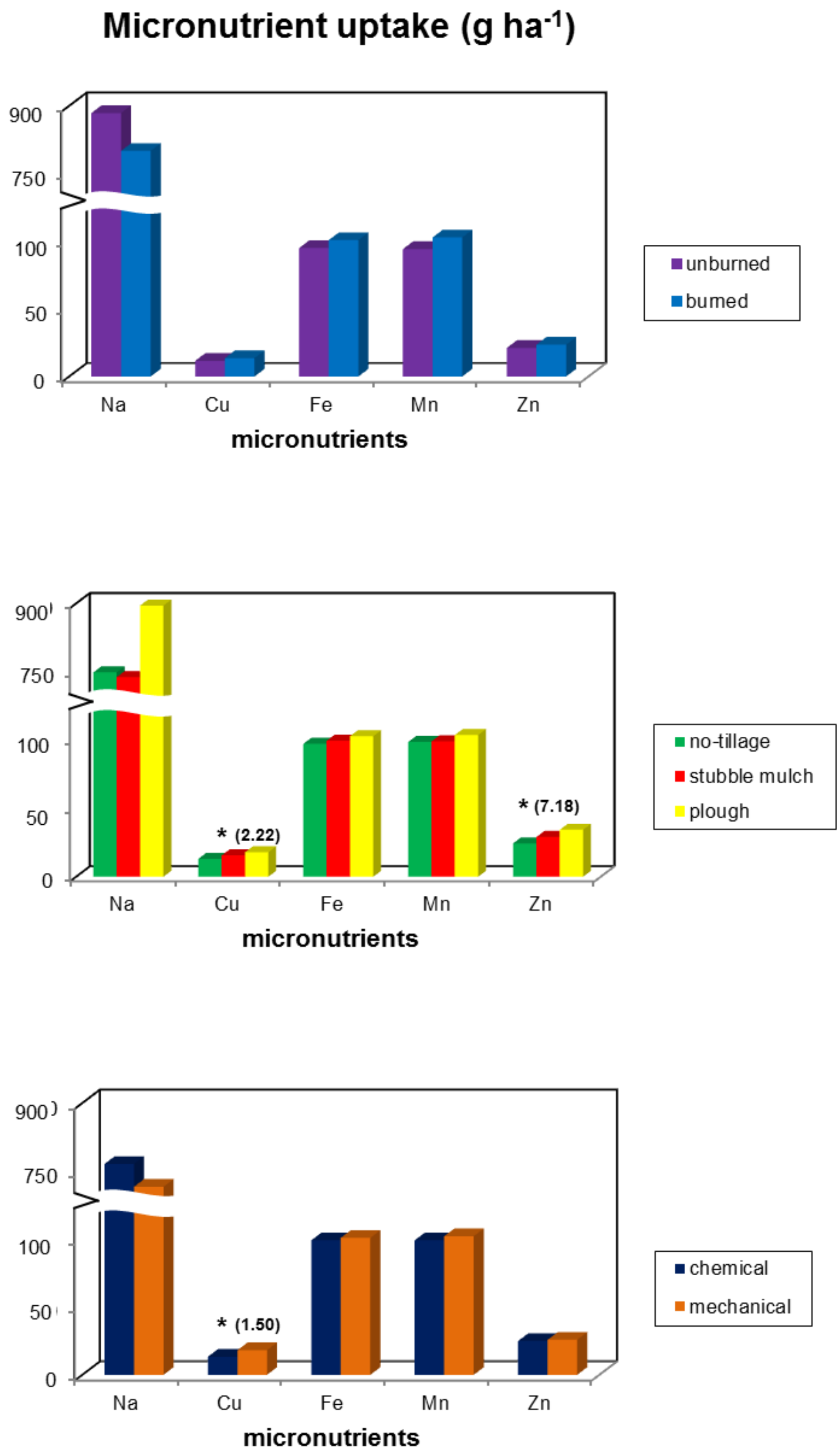

Figure 7.5 Effect of straw disposal, tillage and weed control methods on micronutrient uptake by oat at mid-shooting stage. LSD_T-values are shown where applicable.

A further inspection of Figure 7.4 and 7.5 indicates that weeding methods did not show any significant influence on nutrient uptake except on Cu uptake. The amount of Cu absorbed by oat plants was 9.60 g ha^{-1} in mechanically-weeded plots and 6.44 g ha^{-1} in the chemically-weeded plots. Even though the differences were insignificant between the two weeding methods, mechanical weeding resulted in a slightly higher N, K, S, Mg (Figure 7.4), Fe, Mn and Zn (Figure 7.5) uptake and lower P, Ca (Figure 7.4) and Na (Figure 7.5) uptake when compared with chemical weeding.

Interactions

The interactive effects of different treatment combinations are summarized in Table 7.6. From the summary of analyses of variance (Table 7.5) it is evident that methods of straw disposal combined with tillage significantly influenced P, Cu and Fe uptake, while the interaction between tillage and weeding methods had a significant effect on N, P, Ca and Mg uptake. Irrespective of the method of straw disposal or weeding, mouldboard ploughing increased P uptake more than no-tillage or stubble mulch; however, higher P uptake was observed in unburned or chemically-weeded plots with an LSD_T of 1.35 kg ha^{-1}. The uptake of Cu by oat was also highest (10.60 g ha^{-1}) with mouldboard ploughing combined with unburned straw and least (5.96 g ha^{-1}) under no-tillage combined with the burned straw with an LSD_T of 3.88 g ha^{-1}. A similar pattern was perceived with Fe absorption, though in this particular case the lowest Fe uptake occurred in unburned mulched plots (LSD_T = 48.17 g ha^{-1}). Similarly, mouldboard ploughing when combined with chemical weeding resulted in the highest N, Ca and Mg uptake (LSD_T = 12.64, 1.02 and 1.01 kg ha^{-1} respectively), while the interaction between no-tillage and chemical weeding resulted in the lowest N and Mg absorption and that of mulch tillage and mechanical weeding gave the least Cu uptake. The treatment combinations did not influence the uptake of K, S, Na, Mn and Zn.

The preceding results clearly indicate that no-burning of wheat straw resulted in a higher concentration of Mg, Na, Cu, Zn, N, K and Fe and lower S and Mn content of oat when compared to burning of straw, though not always significant. Low nutrient concentrations of oat in the burned plots can be attributed to higher biomass yield as it influences nutrient applied method of straw disposal. No-tillage enhanced Ca, P, Mg and Mn content, stubble mulch increased the concentration of Cu, Fe and Zn, while mouldboard ploughing elevated N, K, S and Na content of oat. Chemical weeding also increased P, Ca, Na, N and Fe content and reduced Cu, K, S, Mn and Zn content of oat compared with mechanical weeding. Magnesium concentration in oat was the same under both weeding methods. Agbede (2010) found that in both 2006 and 2007, mouldboard ploughing increased leaf N, content in plants. The concentration of P and Ca was, on average, similar in oat despite the

Table 7.6 Effect of the interactions between straw disposal, tillage and weed control methods on nutrient uptake by oat at mid-shooting stage

	N (kg ha^{-1})					P (kg ha^{-1})					K (kg ha^{-1})				
	Tillage			**Weeding**		**Tillage**			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	21.24	16.07	28.72	20.76	23.26	2.62	2.06	3.80	2.79	2.86	35.04	27.12	49.63	32.91	41.61
Burned	19.26	25.88	26.64	23.45	24.40	2.79	3.55	3.75	3.43	3.30	31.43	43.96	46.25	39.28	41.81
Weeding Chemical	15.26	20.03	31.03			2.20	2.93	4.20			23.77	33.08	51.44		
Mechanical	25.25	21.92	24.33			3.21	2.68	3.36			42.70	38.00	44.44		

	S (kg ha^{-1})					Ca (kg ha^{-1})					Mg (kg ha^{-1})				
	Tillage			**Weeding**		**Tillage**			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	1.09	1.67	2.92	1.87	1.91	2.26	1.47	2.92	2.31	2.12	2.11	1.69	2.82	2.05	2.36
Burned	0.99	2.31	3.72	1.59	3.10	2.40	2.48	2.94	2.87	2.34	2.13	2.62	2.76	2.42	2.58
Weeding Chemical	1.09	1.51	2.59			2.00	2.19	3.59			1.61	2.10	2.99		
Mechanical	1.00	2.46	4.05			2.65	1.76	2.27			2.62	2.21	2.58		

	Na (g ha^{-1})					Cu (g ha^{-1})					Fe (g ha^{-1})				
	Tillage			**Weeding**		**Tillage**			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	663.29	542.79	1115.43	925.56	622.10	6.21	7.15	10.60	6.23	9.74	87.83	73.28	123.23	85.44	104.12
Burned	573.12	658.76	669.65	625.63	642.05	5.96	9.69	8.50	6.64	9.46	85.05	122.13	105.46	104.46	103.97
Weeding Chemical	495.43	660.27	1171.09			4.02	6.44	8.85			70.37	95.42	119.05		
Mechanical	740.98	541.27	613.98			8.16	10.40	10.25			102.51	100.00	109.64		

	Mn (g ha^{-1})					Zn (g ha^{-1})				
	Tillage			**Weeding**		**Tillage**			**Weeding**	
	None	Mulch	Plough	Chemical	Mechanical	None	Mulch	Plough	Chemical	Mechanical
Straw Unburned	97.05	67.96	108.41	75.16	107.11	23.26	20.58	32.80	22.19	28.91
Burned	89.76	122.82	128.94	114.58	113.10	21.42	30.86	31.22	26.84	28.82
Weeding Chemical	73.72	97.44	113.46			16.52	24.19	32.82		
Mechanical	113.09	93.34	123.89			28.16	27.24	31.19		

P, K, Ca and Mg concentrations of sweet potato more than no-tillage. Martin-Rueda *et al*. (2007) also indicated higher K, P, Mn and Zn content of barley straw in the ploughed plots compared to minimum or no-tilled plots. However, Cu was higher in barley planted under minimum tillage as opposed to the other two tillage systems. The same authors pointed out that despite the applied tillage practices only Mn concentration in barley was sufficient for optimum growth. Perhaps this could be attributed to the fact that sampling was done at harvest when nutrients were already used for grain yield (Martin-Rueda *et al*., 2007). Du Preez and Bennie (1991; 1992) highlighted that nutrient concentration in wheat decreased with age. They ascribed this to slower nutrient assimilation rates relative to C. Alternatively, Deubel *et al*. (2011) showed that K content in wheat and maize was not affected by tillage, while P concentration in wheat was almost the same, but greater in maize under conservation tillage as opposed to ploughing.

As shown in Table 7.7, irrespective of the applied field treatments concentrations of N, P, K, Ca, Mg, Cu and Zn in the above-ground plant parts were inadequate when the measured minimum, maximum and average concentrations of the latter nutrients are compared to the optimum ranges of Bergmann (1992). Below these optimum ranges plants are likely to suffer acute nutrient deficiencies. Such deficiencies can lead to stunted crop growth and eventually poor yield. In contrast, Mn content and the maximum value of Cu content were adequate for oat at mid-shooting stage.

On the contrary to nutrient concentration in oat, straw burning resulted in a higher (although not always significant) uptake of N, P, K, S, Ca, Mg, Cu, Fe, Mn and Zn by oat plants when compared to no- burning. This could possibly be due to reduced microbial nutrient immobilization following residue burning (Kumar & Goh, 2002; Yadvinder-Singh *et al*., 2005; Bhupinderpal-Singh & Rengel, 2007). Unburned straw, on the other hand, improved Na absorption when compared to burned treatments. These findings are more or less similar to those reported by other research workers. Kumar and Goh (2002) showed that among non-leguminous residues, significantly higher N uptake was observed in the burned plots than in unburned plots. However, among the applied treatments, the same authors revealed that unburned crop residues increased N uptake significantly when compared to the burned crop residues. Bakht *et al*. (2009) also reported higher N uptake by wheat under the residue retained treatments than under the residue removed plots and this was accredited to the rotational benefits of a legume on a succeeding wheat crop. In a two-year field experiment on an Oxic Paleudult, it was found that nutrient uptake in 1993, particularly for N and P was greater in the burned treatments than in the residue incorporated treatments, especially when no fertilizer was applied (Adetunji, 1997). Conversely, in 1994 absorption of N, P, K, Mg, Ca and S was highest in the residue incorporated plots, followed by the burned plots and then the bare plots.

Table 7.7 Measured and optimum concentration values for nutrients in oat at mid-shooting stage

	Measured values			
Nutrient	**Minimum**	**Maximum**	**Average**	**Optimum ranges***
N (%)	1.27	1.50	1.38	2.20 – 350
P (%)	0.17	0.20	0.19	0.28 – 0.50
K (%)	2.08	2.54	2.31	3.80 – 5.00
S (%)	0.06	0.21	0.12	–
Ca (%)	0.11	0.18	0.15	0.40 – 1.00
Mg (%)	0.14	0.15	0.14	0.15 – 0.25
Na (mg kg^{-1})	331.39	590.56	422.08	–
Cu (mg kg^{-1})	3.58	6.72	4.85	5.00 –10.00
Fe (mg kg^{-1})	52.92	64.20	60.39	–
Mn (mg kg^{-1})	54.03	69.50	62.24	35.00–100.00
Zn (mg kg^{-1})	14.19	17.69	16.10	20.00 – 70.00

*****Bergmann (1992)

Among the applied tillage practices, mouldboard ploughing showed a positive influence on the uptake of all the studied nutrients as well as on biomass yield when compared to stubble mulch and no-tillage. These observations (especially for nutrient uptake) are in contrast to the findings of some researchers (Mozafar *et al*., 2000; Lupwayi *et al*., 2006b). Malhi and Lemke (2007) reported significantly higher straw and chaff yield for barley in 2002 under no-tillage compared to ploughing. The opposite was observed in 2005 for canola straw yield.

Compared to chemical weeding, mechanical weeding led to a higher uptake of N, K, S, Mg, Cu, Fe, Mn and Zn as well as biomass yield, and a decline in the absorption of P, Ca and Na. These results, to some extent, are not surprising because paraquat is known to negatively affect bacterial population in the soil (Sahid *et al*., 1992), and that can result in low nutrient mineralization rates, hence reduced nutrient availability to plants. Tu and Bollen (1968) revealed that application of paraquat to four different soils did not affect nitrification, but slightly retarded ammonification of organic N. In a nutshell, higher nutrient uptake under mechanical weeding could be due to higher soil organic matter, which plays an important role in water and nutrient conservation.

Based on the results obtained in this study, it is obvious that high concentration of nutrients in the soil does not necessarily imply that such nutrients are available for plant uptake. This is derived from the fact that most of the investigated soil fertility indicators were on average higher under conservation tillage systems as opposed to ploughing, but the opposite is true with regard to nutrient uptake and dry matter. Therefore high nutrient uptake and biomass yield under mouldboard ploughing and to some extent under mechanical weeding could be ascribed to reduced nutrient immobilization and crop emergence problems resulting from ideal soil environment for seedling establishment and homogenous distribution of nutrients. Deubel *et al*. (2011) concluded that apparently plants grown under conservation tillage practices do not make use of nutrients concentrated in the surface soil sufficiently. Therefore maybe one-time tillage of no-tilled soil once after 10 years as suggested by Garcia *et al*. (2007) can be practised to reduce accumulation of nutrients in the topsoil and improve their uptake by plants, especially if some indicators like soil organic matter would not be negatively affected. Nutrient accumulation in plants however, still remains subject to the ability of plants to absorb nutrients and make use of them efficiently. For example, in a greenhouse experiment it was found that two lupin species were less effective in the absorption of K than canola and wheat, but were more efficient in converting the absorbed K to produce shoots when compared to canola and wheat (Brennan & Bolland, 2004).

7.2.2 Grain yield of wheat from 1979 to 2010

Grain yield data presented in this study are from 1979 to 2010; however, in some seasons (1980, 1981, 1990, 1992, 2004 and 2010) no grain yield data were recorded due to oat being planted and/or drought. The 31 growing seasons were then divided into 11 years (1979-1990), 10 years (1991-2000) and 10 years (2001-2010), which basically correspond with the period intervals at which soil fertility indicators were measured. The overall (1979-2010) grain yield data are also included. Therefore as indicated in the summary of analyses of variance (Table 7.8), tillage and straw disposal methods influenced wheat grain yield more than weeding. The combination between methods of straw disposal and tillage also had a significant effect on grain yield although only in the 2001-2010 period.

Main effects

No-burning of straw increased wheat grain yield when compared to straw burning; however, significant differences were observed only in the 1979-2010, 1979-1990 and 2001-2010 period intervals (Figure 7.7). The average grain yield ranged from 2.12 to 2.28 t ha^{-1} in the 1979-2010 period, from 1.99 to 2.19 t ha^{-1} in the 1979-1990 period and from 2.25 to 2.47 t ha^{-1} in the 2001-2010 period. Adetunji, (1997) also reported that in 1994, maize yield was

Table 7.8 Summary of analyses of variance indicating the significant effects of straw disposal, tillage and weed control methods on wheat grain yield at a 95% confidence level

	Wheat grain yield			
Treatments[a]	**1979-2010**	**1979-1990**	**1991-2000**	**2001-2010**
A	*	*		*
B	*	*	*	*
AB				*
C				
AC				
BC				
ABC				

[a]A: straw disposal, B: tillage, C: weeding

higher in the unburned plots (residue incorporated) than in the burned or bare plots. These results are contradictory to those obtained by Chan and Heenan (2005) who detected significantly higher wheat grain yield under straw burning when compared to no-burning.

Tillage practices affected grain yield significantly throughout the considered period intervals (Figure 7.7). In the 1979-2010, 1979-1990 and 1991-2000 periods, grain yield was highest (2.28, 2.16 and 2.02 t ha^{-1}, respectively) in the ploughed plots, intermediate (2.19, 2.07 and 1.90 t ha^{-1}) in the mulched plots and lowest (2.11, 2.04 and 1.85 t ha^{-1}) in no-tilled plots. In the period of 2001-2010, mouldboard ploughing resulted in the highest grain yield (2.46 t ha^{1}), followed by no-tillage (2.33 t ha^{-1}) and then stubble mulch (2.29 t ha^{-1}). Better soil conditions and homogeneous distribution of nutrients could be the reason for higher yields under mouldboard ploughing. However, in 2002, Malhi and Lemke (2007) found higher barley grain yield in no-tilled plots as opposed to the ploughed plots, but in 2005 the opposite was found with canola. In Wagga Wagga Australia, wheat grain yield was found to be significantly higher under no-tillage as compared to mouldboard ploughing (Chan & Heenan, 2005). This suggests that no-tillage has a potential to enhance crop productivity, particularly if problems associated with nutrient immobilization and diseases can be addressed.

No significant effects could be found on wheat grain yield due to weeding methods (Figure 7.7). Nevertheless, it can be pointed out that chemical weeding tended to increased grain yield in the 1979-2010, 1991-2000 and 2001-2010 periods when compared to mechanical

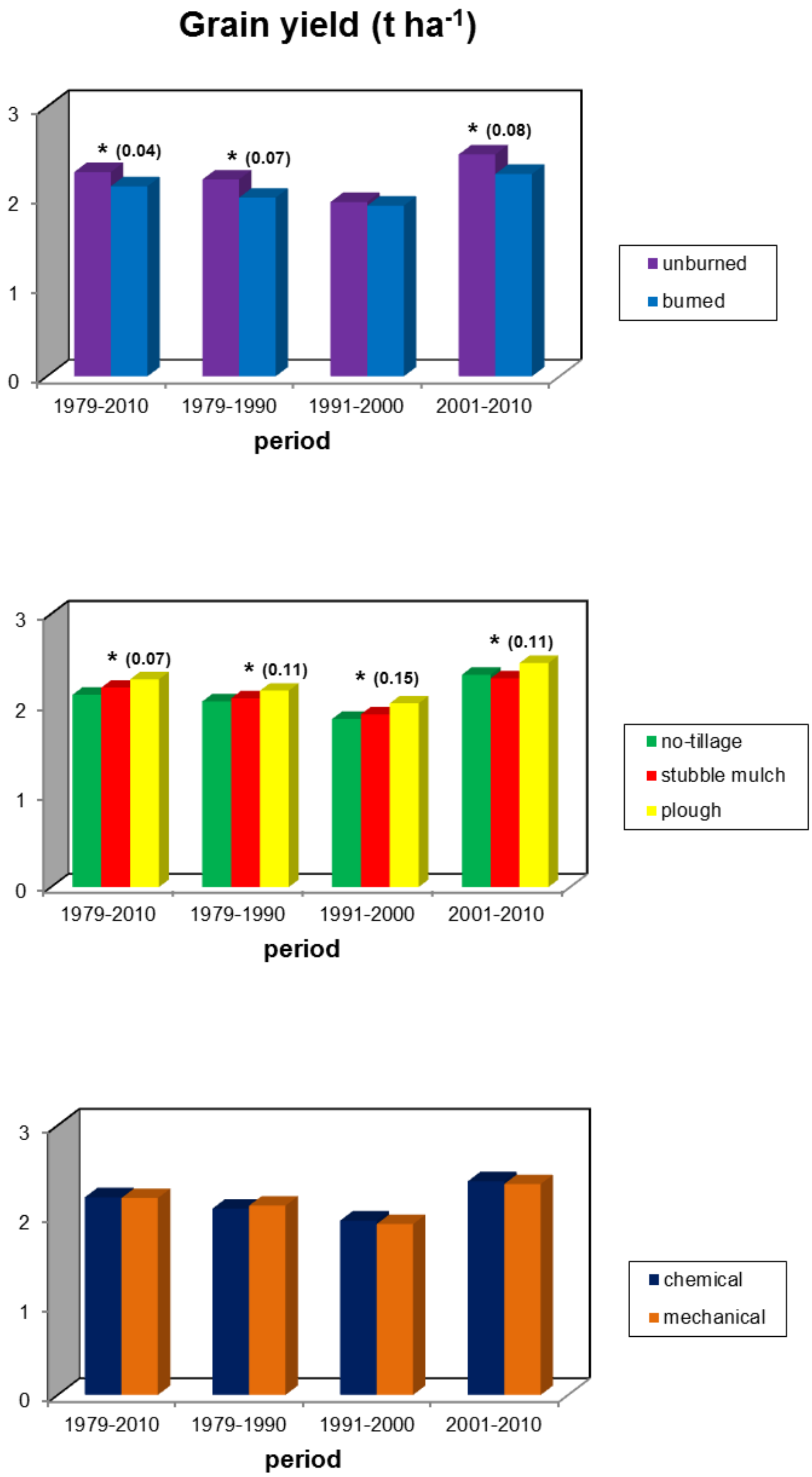

Figure 7.6 Effect of straw disposal, tillage and weed control methods on wheat grain yield. LSD_T-values are shown where applicable.

weeding. In the 1979-1990 period, on the contrary, a slightly higher grain yield was recorded in mechanically-weeded plots rather than in the chemically-weeded plots.

Interactions

The effects of interactions between different treatments on wheat grain yield are presented in Table 7.9. As can be seen in the summary of analyses of variance (Table 7.8), the combination between tillage and straw disposal methods had a significant effect on grain yield only in the 2001-2010 period (LSD_T = 0.20 t ha^{-1}). Compared to straw burning, no-burning of straw in the ploughed, mulched or no-tilled plots resulted in a higher grain yield; however, a significant difference was noticed in mulched treatments.

Table 7.9 Effect of the interactions between straw disposal, tillage and weed control methods on wheat grain yield (t ha^{-1})

		Tillage			Weeding	
		None	Mulched	Ploughed	Chemical	Mechanical
1979-2010						
Straw	Unburned	2.18	2.29	2.35	2.28	2.27
	Burned	2.04	2.10	2.21	2.12	2.11
Weeding	Chemical	2.10	2.19	2.31		
	Mechanical	2.12	2.20	2.26		
1979-1990						
Straw	Unburned	2.13	2.19	2.26	2.17	2.21
	Burned	1.95	1.96	2.06	1.98	2.00
Weeding	Chemical	1.97	2.06	2.20		
	Mechanical	2.11	2.09	2.12		
1991-2000						
Straw	Unburned	1.86	1.90	2.06	1.93	1.96
	Burned	1.83	1.90	1.97	1.95	1.85
Weeding	Chemical	1.88	1.94	2.01		
	Mechanical	1.81	1.86	2.03		
2001-2010						
Straw	Unburned	2.46	2.46	2.50	2.51	2.44
	Burned	2.21	2.13	2.43	2.25	2.26
Weeding	Chemical	2.36	2.27	2.50		
	Mechanical	2.30	2.32	2.42		

Methods of straw disposal combined with tillage did not significantly affect grain yield in the other periods. Similarly, no significant effects were observed in the combination between tillage and weeding methods as well as methods of straw disposal and tillage; however, some interesting trends emerged. Mouldboard ploughing increased grain yield throughout the considered periods when compared to either stubble mulch or no-tillage regardless of the applied weeding method. Nevertheless, higher grain yield was recorded in the chemically-weeded plots than in mechanically-weeded plots. Grain yield was also found to be higher in unburned treatments than in the burned plots despite the employed weeding method. Even so, chemical weeding resulted in a higher grain yield in the 1979-2010 and 2001-2010 periods and lower grain yield in the 1979-1990 and 1991-2000 periods when compared to mechanical weeding.

Despite the applied field treatments, wheat grain yield in the 2001-2010 period was slightly higher than grain yield recorded in the 1979-1990 and 1991-2000 periods (Figure 7.6). Surprisingly, rainfall in the former period (2001-2010) was lower compared to that in other periods, especially during the growing season (Table 7.10). Perhaps rainfall did not have a large effect on grain yield. On the other hand, these changes in grain yield could be due to various factors such as improved soil water storage, timing of cultivation, improved planting method with the new planter and greater genetic potential and adaptation of the new cultivar Elands. In the last 10 years of this trial also, some soil fertility indicators (organic C, total N, P, K, Cu, Fe, Mn and Zn) declined when the 1999 study by Kotzé (2004) served as a reference. It is therefore assumed that a decline in such soil fertility indicators was due to higher wheat grain yield recorded within those years (2001-2010 period).

Table 7.10 Summary of seasonal rainfall data corresponding with period intervals for wheat grain yield data (ARC-ISCW, 2011)

	Rainfall (mm)			
Season	**1979-2010**	**1979-1990**	**1991-2000**	**2001-2010**
Fallow: Jan-Jun	1678.33	501.83	655.75	520.75
Growing: Jul-Dec	1606.95	562.30	609.19	435.46
Annual: Jan-Dec	3285.28	1064.13	1264.94	956.21

7.3 Conclusion

Straw burning increased nutrient uptake and biomass yield by oat plants, but reduced wheat grain yield when compared to no-burning. Despite higher nutrient accumulation under no-tillage and stubble mulch, mouldboard ploughing improved nutrient uptake as well as biomass and grain yield. Mechanical weeding also showed a positive influence on nutrient absorption and biomass yield as opposed to chemical weeding. Chemical weeding, on the contrary, showed a potential to enhance grain yield. Among the treatment combinations, mouldboard ploughing combined with either unburned straw or chemical weeding resulted in high nutrient uptake and wheat grain yield. Therefore it can be concluded that mouldboard ploughing is a viable measure to improve crop productivity. Conservation practices can also produce comparable results if problems associated with microbial nutrient immobilization can be dealt with.

CHAPTER 8

Summary and recommendations

The most dominant forms of soil fertility deterioration on cropped soils in the Free State Province are erosion, acidification and organic matter degradation (Hensley *et al*., 2006). However, emerging evidence has shown that management practices that ensure large amounts of crop residues to be returned to the soil after harvesting can alleviate these problems. Therefore the objectives of this study were to: (1) evaluate the effects of different wheat residue management practices after 30 years on some soil fertility indicators, (2) compare the 30 year results of soil fertility indicators with the 20 year and 10 year results where possible, (3) establish whether nutrient uptake by plants was influenced by the nutrient stratification resulting from 30 years of different wheat residue management practices and (4) determine whether wheat grain yield over the 30 years was affected by different wheat residue management practices.

This study was conducted in a long-term wheat trial at the ARC-Small Grain Institute near Bethlehem in the Eastern Free State on an Avalon soil, where two methods of straw disposal, three methods of tillage and two methods of weed control have been applied since 1979. To accomplish the objectives of this study, soil sampling was done in 2010 at various soil depths inside and outside the trial. At mid-shooting stage plant samples were collected to determine nutrient uptake. Yield data was supplied by ARC-Small Grain Institute.

Organic C, total N and total S as soil organic matter indices were affected differently by methods of straw disposal and tillage. Unburned straw increased total N and S, but resulted in lower organic C contents when compared to the burned straw. No-tillage resulted in a higher organic C content only in the 0-50 mm soil layer compared to stubble mulch and mouldboard ploughing. Below a soil depth of 100 mm, organic C was higher in the ploughed plots than in the mulched or no-tilled plots. No-tillage and stubble mulch enhanced total N more than mouldboard ploughing. In contrast, ploughing and to some extent stubble mulch increased total S in the upper 150 mm soil depth. Surprisingly, mechanical weeding improved organic matter content of this Avalon soil more than chemical weeding.

Soil pH as a measure of acidity was influenced more by tillage practices than methods of straw disposal or weeding. No-tillage and stubble mulch resulted in a higher soil pH in the upper 100 mm and lower 350-450 mm soil depths than mouldboard ploughing. The opposite is true in the other three middle soil layers. Mechanical weeding suppressed soil acidification when compared to chemical weeding. Methods of straw disposal had variable effects on soil pH. Unburned straw slightly increased soil pH to a soil depth of 100 mm when compared with the burned straw. The trend changed below 100 mm soil depth. No-tillage combined with either chemical weeding or burned straw appeared to be effective in ameliorating acidity in the surface soil, whereas mechanical weeding combined with either no-tillage or ploughing retarded subsoil acidity.

Straw burning resulted in a higher P, K and Mg as well as lower Ca and Na contents as opposed to no-burning of straw. Cation exchange capacity was slightly higher in the upper two soil layers and deepermost soil layer of unburned plots when compared to the burned plots. No-tillage increased the concentration of P, K, Ca, Mg and Na, especially in the upper soil layers, when compared to other two tillage methods. Cation exchange capacity decreased as tillage intensity increased. Chemical weeding improved P, K, Mg, Na and CEC, but not Ca when compared to mechanical weeding.

The burned plots had higher Mn and Zn contents when compared to unburned plots. Unburned straw, on the other hand, increased the concentration of Cu when compared to the burned straw. Methods of straw disposal had insignificant and inconsistent effects on Fe that are not worth mentioning. The applied tillage practices also had variable effects on micronutrient cations; however, it can be pointed out that no-tillage and stubble mulch resulted in an accumulation of Fe and Zn, but lower Cu relative to mouldboard ploughing. Mechanically-weeded plots had higher contents of micronutrient cations than chemically-weeded plots, and this could be explained by higher organic matter content in the former.

In general, results of this study more or less resemble those obtained in 1989/1990 (Du Preez *et al*., 2001) and 1999 (Kotzé, 2004); however, in the current study the magnitude of some of the investigated soil fertility indicators (organic C, total N, P, K, Cu, Fe, Mn and Zn) declined when the previous studies (Du Preez *et al*., 2001; Kotzé, 2004) served as references. The reasons to this phenomenon are not known, but fluctuating climate could be one of them, or else increased wheat grain yield within the last 10 years of this trial could be attributable to this response. Furthermore, soil organic matter inside the trial was lower than that in the headlands. As a result, CEC and some nutrients such as Ca, Mg, Na, Cu, Fe, Mn and Zn declined. This is indicative that irrespective of the applied residue management, cropping depletes organic matter, and ultimately soil nutrients.

The burned straw increased nutrient uptake by oat, but resulted in a lower grain yield when compared to unburned straw. Nutrient uptake and wheat grain yield increased with an increase in tillage intensity. Mechanical weeding improved nutrient uptake, but not wheat grain yield when compared with chemical weeding. Mouldboard ploughing combined with either unburned straw or chemical weeding resulted in a higher nutrient uptake and grain yield. However, irrespective of higher nutrient uptake in the burned, ploughed or mechanically-weeded plots the concentrations of nutrients, except for Mn, in oat plants at mid-shooting stage were below optimum levels. This indicates that oat was already or likely to suffer acute nutrient deficiencies at a later stage.

Based on the preceding results the following recommendations can be made:

- It seems possible to maintain or even improve organic matter content, nutrient content and CEC as well as to curb acidification in this Avalon soil with the use of no-tillage and stubble mulch rather than mouldboard ploughing. However, higher nutrient uptake and grain yield were recorded with mouldboard ploughing instead of no-tillage or stubble mulch. Better conditions for water storage and an even distribution of nutrients under mouldboard ploughing could be attributed to this response.

- Perhaps, evaluation of crop residue management effects on various nutrient fractions (organic, inorganic and microbial) can provide a better understanding on the ability of no-tillage and stubble mulch to improve soil fertility but fail to enhance nutrient uptake and grain yield.

- The influence of different residue management practices on nutrient uptake or content has been ignored since the initiation of this trial. Therefore, since this was the first investigation into this matter, future investigations would be very interesting.

REFERENCES

ADETUNJI, M.T., 1997. Organic residue management, soil nutrient changes and maize yield in a humid ultisol. *Nutr. Cycl. Agroecosyst*. 47, 189-195.

AGBEDE, T.M., 2010. Tillage and fertilizer effects on some soil properties, leaf nutrient concentrations, growth and sweet potato yield on an Alfisol in southwestern Nigeria. *Soil Till. Res*. 110, 25-32.

AL-KAISI, M & LICHT, M.A., 2004. Effect of strip tillage on corn nitrogen uptake and residual soil nitrate accumulation compared with no-tillage and chisel plow. *Agron*. *J.* 96,1164-1171.

ARC-ISCW, 2011. Agrometeorological data base. ARC-institute for Soil, Climate and Water, Pretoria

AYANSINA, A.D.V. & OSO, B.A., 2006. Effect of two commonly used herbicides on soil microflora at two different concentrations. *Afr*. *J*. *Biotech*. 5, 129-132.

BAKHT, J., SHAFI, M., JAN, M.T. & SHAH, Z., 2009. Influence of crop residue management, cropping system and N fertilizer on soil N and C dynamics and sustainable wheat (*Triticum aestivum* L.) production. *Soil Till*. *Res*. 104, 233-240.

BARNARD, R.O. & DU PREEZ, C.C., 2004. Soil fertility in South Africa: the last twenty five years. *S. Afr. J. Plant Soil* 21, 301-315.

BEN MOUSSA-MACHRAOUI, S., ERROUISSI, F., BEN-HAMMONDA, M. & NOUIRA, S., 2010. Comparative effects of conventional and no-tillage management on some soil properties under Mediterranean semi-arid conditions in northwestern Tunisia. *Soil Till*. *Res*. 106, 247-253.

BERGMANN, W., 1992. Nutritional disorders of plants: Development, visual and analytical diognosis. VCH Publishers Inc., 303 N.W. 12th Avenue, Deerfield Beach, Florida.

BHUPINDERPAL-SINGH & RENGEL, Z., 2007. The role of crop residues in improving soil fertility. *In*: P. Marschner & Z. Rengel (eds). Soil biology: Nutrient cycling in terrestrial ecosystems. Springer-Verlag, Berlin.

BIJAY-SINGH, SHAN, Y.H., JOHNSON-BEEBOUT, S.E., YADVINDER-SINGH & BURESH, R.J., 2008. Crop residue management for lowland rice-based cropping systems in Asia. *Adv*. *Agron*. 98, 117-199.

BRENNAN, R.F. & BOLLAND, M.D.A., 2004. Lupin takes up less potassium but uses the potassium more effectively to produce shoots than canola and wheat. *Aust. J. Exp. Agric*. 44, 309-319.

CALEGARI, A., HARGROVE, W.L., RHEINHEIMER, D.S., RALISCH, R., TESSIER, D. DE TOURDONNET, S. & GUIMARÃES, M.F., 2008. Impact of long-term no-tillage and cropping system management on soil organic carbon in an Oxisol: A model for sustainability. *Agron. J*. 100, 1013-1019.

CHAN, K.Y. & HEENAN, D.P., 2005.The effects of stubble burning and tillage on soil carbon sequestration and crop productivity in southeastern Australia. *Soil Use Manage.* 21, 427-431.

CHEN, H., HOU, R., GONG, Y., LI, H., FAN, M. & KUZYAKOV, Y., 2009. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. *Soil Till*. *Res*. 106, 85-94.

CHIVENGE, P.P., MURWIRA, H.K., GILLER, K.E., MAPFUMO, P. & SIX, J., 2007. Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil Till. Res*. 94, 328-337.

DALAL, R.C., ALLEN, D.E., WANG, W.J., REEVES, S. & GIBSON, I., 2011. Organic carbon and total nitrogen stocks in a Vertisol following 40 years of no-tillage, crop residue retention and nitrogen fertilisation. *Soil Till. Res*. 112, 133-139.

DE SANTIAGO, A., QUINTERO, J.M. & DELGADO, A., 2008. Long-term effects of tillage on the availability of iron, copper, manganese, and zinc in a Spanish Vertisol. *Soil Till*. *Res*. 98, 200-207

DEUBEL, A., HOFMANN, B. & ORZESSEK, D., 2011. Long-term effects of tillage on stratification and plant availability of phosphate and potassium in a loess chernozem. *Soil Till. Res*. 117, 85-92.

DU PREEZ, C.C. & BENNIE, A.T.P., 1991. Concentration, accumulation and uptake rate of macro-nutrients by wheat under irrigation*. S. Afr. J. Plant Soil*. 8, 31-37.

DU PREEZ, C.C. & BENNIE, A.T.P., 1992. Concentration, accumulation and uptake rate of Cu, Fe, Mn and Zn by wheat under irrigation. *S. Afr. J. Plant Soil. 9, 4-9*.

DU PREEZ, C.C., STEYN, J.T. & KOTZÉ, E., 2001. Long-term effects of wheat residue management on some fertility indicators of a semi-arid Plinthosol. *Soil Till*. *Res*. 63, 25-33.

DU PREEZ, C.C., VAN HUYSSTEEN, C.W. & MNKENI, P.N.S., 2011a. Land use and soil organic matter in South Africa 1: A review on spatial variability and the influence of rangeland stock production. *S. Afr. J. Sci*. 107, 27-34.

DU PREEZ, C.C., VAN HUYSSTEEN, C.W. & MNKENI, P.N.S., 2011b. Land use and soil organic matter in South Africa 2: A review on the influence of arable crop production. *S. Afr. J. Sci*. 107, 35-42.

ERIKSEN, J., 2009. Soil sulfur cycling in temperate agricultural systems. *Adv*. *Agron*. 102, 55-89.

FAO, 1978. World reference base for soil resources. World resources Report No. 84 FAO, Rome.

GAFUR, A., KOCH, C.B. & BORGGARD, O.K., 2004. Weathering intensity controlling sustainability of Ultisols under shifting cultivation in Chittagong Hill Tracks of Bangladesh. *Soil Sci.* 169, 663-674.

GARCIA, J.P., WORTMANN, C.S., MAMO, M., DRIJBER, R. & TARKALSON, D., 2007. One-time tillage of no-till: effects on nutrients, mycorrhizae, and phosphorus uptake. *Agron. J.* 99, 1093-1103.

GLENDINNING, J.S., 2000. Australian soil fertility manual. Fertilizer Industry Federation of Australia, Inc. & CRISO.

HAVLIN, F.L., BEATON, J.D., TISDALE, S.L. & NELSON, W.L., 1999. Soil fertility and fertilizers: an introduction to nutrient management. 6^{th} edn, Prentice Hall, New Jersey.

HEARD, J., CAVERS, C. & ADRIAN, G., 2006. Up in smoke-nutrient loss with straw burning. *Better Crops.* 90, 10-11.

HENSLEY, M., LE ROUX, P., DU PREEZ, C.C., VAN HUYSSTEEN, C., KOTZÉ, E. & VAN RENSBURG, L., 2006. Soil: The Free State's agricultural base. *S. Afr. Geo. J*. 88, 11-21.

HILLER, E., FARGASOVA, A., ZEMANOVA, L. & BARTAL, M., 2007. Influence of wheat ash on the MCPA immobilization in agricultural soils. *Bull. Environ. Contam. Toxicol.* 78, 345-348.

HINTZE, J.L., 1997. Number cruncher statistical systems 2000, Kaysville, Utah.

HOUX III, J.H., WIEBOLD, W.J. & FRITSCHI, F.B., 2011. Long-term tillage and crop rotation determines the mineral nutrient distributions of some elements in a Vertic Epiaqualf. *Soil Till. Res.* 112, 27-35.

HUBER, D., 2010. What’s new in Ag chemical and crop nutrient interaction. http:www.fluidjournal.org/1gsdgfs-S10/S10-A4.pdf (Accessed 21-07-2011).

ITANNA, F., 2005. Sulfur distribution in five Ethiopian Rift Valley soils under humid and semi-arid climate. *J. Arid Environ*. 62, 597-612.

KOTZÉ, E., 2004. Influence of long-term wheat residue management on some fertility indicators of an Avalon soil at Bethlehem. M.Sc. Thesis, University of the Free State, Bloemfontein, South Africa.

KOTZÉ, E. & DU PREEZ, C.C., 2007. Influence of long-term wheat residue management on organic matter in an Avalon soil. *S. Afr. J. Plant Soil*. 25, 14-21.

KOTZÉ, E. & DU PREEZ, C.C., 2008. Influence of long-term wheat residue management on acidity and some macronutrients in an Avalon soil. *S. Afr. J. Plant Soil*. 25, 14-21.

KRISHNA, K.R., 2002. Nutrient dynamics in agro-environments. *In*: K.R. Krishna (ed). Soil fertility and crop production. Science Publishers Inc., Enfield, USA.

KUMAR, K. & GOH, K.M., 2002. Management practices of antecedent leguminous and non-leguminous crop residues in relation to winter wheat yields, nitrogen uptake, soil nitrogen mineralization and simple nitrogen balance. *Eur. J. Agron.* 16, 295-308.

KUTCHER, H.R. & MALHI, S.S., 2010. Residue burning and tillage effects on diseases and yield of barley (*Hordeum vulgare*) and canola (*Brassica napus*). *Soil Till. Res*. 109, 153-160.

LAL, R., 2005. World crop residues production and implications of its use as a biofuel. *Environ*. *Int*. 30, 855-892.

LAL, R., 2009. Soil quality impacts of residue removal for bioethanol production. *Soil.Till*. *Res*. 102, 233-241.

LAND TYPE SURVEY STAFF, 2001. Land types of South Africa. ARC-Institute for Soil, Climate and Water, Pretoria.

LEMKE, R.L., VANDENBYGAART, A.J., CAMPBELL, C.A., LAFOND, C.P. & CRANT, B., 2010. Crop residue removal and fertilizer N: Effects on soil organic carbon in a long-term crop rotation experiment on an Udic Boroll. *Agric. Ecosys. Environ*. 135, 42-51.

LIANG, B., LEHMANN, J., SOLOMON, D., KINYANGI, J., GROSSMAN, J., O'NEILL, B., SKJEMSTAD, J.O., THIES, J., LUIZAO, F.J., PETERSEN, J. & NEVES, E., 2006. Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.* 70, 1719-1730.

LIMOUSIN, G. & TESSIER, D., 2007. Effects of no-tillage on chemical gradients and top soil acidification. *Soil Till. Res*. 92, 167-174.

LÓPEZ-FANDO, C. & PARDO, M.T., 2009. Changes in soil chemical characteristics with different tillage practices in semi-arid environment. *Soil Till. Res*. 104, 278-284.

LUPWAYI, N.Z., CLAYTON, G.W., O'DONOVAN, J.T., HARKER, K.N., TURKINGTON, T.K. & SOON, Y.K., 2006a. Potassium release during decomposition of crop residues under conventional and zero tillage. *Can. J. Soil Sci.* 86, 437-480.

LUPWAYI, N.Z., CLAYTON, G.W., O'DONOVAN, J.T., HARKER, K.N., TURKINGTON, T.K. & SOON, Y.K., 2006b. Soil nutrient stratification and uptake by wheat after several years of conventional and zero tillage in the Northern Grain belt of Canada. *Can. J. Soil Sci*. 86, 767-778.

MACVICAR, C.N., DE VILLIERS, J.M., LOXTON, R.F., VERSTER, E., LAMBRECHTS, J.J.N., MERRYWEATHER, F.R., LE ROUX, J., VAN ROOYEN, T.H. & HARMSE, H.J., 1977. Soil Classification: a binomical system for South Africa. Department Agriculture Technical Services Science Bulletin No. 390, Pretoria.

MALHI, S.S. & KUTCHER, H.R., 2007. Small grains stubble burning and tillage effects on soil organic carbon and nitrogen and aggregation in northeeastern Saskatchewan. *Soil Till*. *Res*. 94, 353-361.

MALHI, S.S. & LEMKE, R., 2007. Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle. *Soil Till. Res*. 96, 269-283.

MANDAL, K.G., MISRA, A.K., HATI, K.M., BANDYOPADHYAY, K.K. GHOSH, P.K. & MOHANTY, M., 2004. Rice residue management options and effects on soil properties and crop productivity. *Food*, *Agric*. & *Environ*. 2, 224-231.

MARTIN-RUEDA, I., MUÑOZ-GUERRA, L.M., YUNTA, F., ESTEBAN, E., TENORIO, J.L. & LUCENA J.J., 2007. Tillage and crop rotation effects on barley yield and soil nutrients on a Calciortidic Haploxeralf. *Soil Till*. *Res*. 92, 1-9.

MBAH, C.N. & NNEJI, R.K., 2010. Effect of different crop residue management techniques on selected soil properties and grain production of maize. *J. App. Sci. Res.* 6, 151-155.

MENZIES, N.W. & GILLMAN, G.P., 2003. Plant growth limitation and nutrient loss following piled burning in slash and burn agriculture. *Nutr. Cycl. Agroecosyst.* 65, 23-33.

MILLS, A.F. & FEY, M.V., 2003. Declining soil quality in South Africa: effects of land use on soil organic matter and surface crusting. *S. Afr. J. Plant Soil*. 99, 429-436.

MOKWUNYE, A.U., KWESIGA, F.R., NDIRITU, C.G. & WOOMER, P.L., 1997. Soil fertility replenishment in Africa: An investment in natural resource capital. p. 1-46. *In*: R.J. Buresh, P.A. Sanchez & F. Calhoun (eds). Replenishing soil fertility in Africa. Soil Science Society America & American Society Agronomy Inc. Madison.

MOZAFAR, A., ANKEN, T., RUH, R. & FROSSARD, E., 2000. Tillage intensity, mycorrhizal and non-mycorrhizal fungi, and canola. *Agron. J*. 92, 1117-1124.

MUUKKONEN, P., HARTIKAINEN, H., LANTI, K. SARKELA, A. PUUSTINEN, M. & ALAKUKKU, L., 2006. Influence of no-tillage on distribution and lability of phosphorus in Finnish clay soils. *Agric*. *Ecosys*. *Environ*. 120, 299-306.

NDIAYE, J.P. & KRISHNA, K.R., 2002. Micronutrients in soil, their acquisition mechanisms and influence on crop growth and yield. *In*: K.R. Krishna (ed). Soil fertility and crop production. Science Publishers, Inc. Enfield, USA.

PARDO, G., ALBAR, J., CIRA, P., LACASTA, C., LEZAÚN, J.A. & ZARAGOZA, C., 2011. Organic versus conventional methods of fertilization and weeding control in a long-term rotation of cereals in semi-arid Spain. *Chilean J. Agric. Res*. 72, 187-194.

QASEM, J.R., 2007. Chemical control of wild-oat (*Avena sterilis* L.) and other weeds in wheat (*Tricium durum* Desf.) in Jordan. *Crop Prot.* 26, 1315-1324.

RENGEL Z., 2007. Cycling of micronutrients in terrestrial ecosystems. *In*: P. Marschner & Z. Rengel (eds). Soil biology: Nutrient cycling in terrestrial ecosystems. Spinger-Verlag, Berlin.

SAHID, I., HAMZAH, A. & ARIS, P.M., 1992. Effects of paraquat and alachlor on soil microorganisms in peat soil. *Pertanika*. 15, 121-125.

SCHERER, H.W., 2001. Sulphur in crop production – invited paper. *Eur. J. Agron*. 14, 81-111.

SCHOMBERG, H.H., FORD, P.B. & HARGROVE, W.L., 1994. Influence of crop residues on nutrient cycling and soil chemical properties. *In*: P.W. Unger (ed). Managing agricultural residues. Lewis Publishers, Boca Raton, FL, USA.

SHAFI, M., BAKHT, J., JAN, M.T. & SHAH, Z., 2007. Soil C and N dynamics and maize (*Zea may* L.) yield as affected by cropping systems and residue management in North-western Pakistan. *Soil Till. Res.* 94, 520-529.

SHARMA, P.K. & MISHRA, B., 2001. Effect of burning rice and wheat residues: Loss of N, P, K and S from soil and changes in the nutrient availability. *J. Ind. Soc. Soil Sci*. 49, 425-429.

SOIL CLASSIFICATION WORKING GROUP, 1991. Soil classification-a taxonomic system for South Africa. Mem. Agric. Nat. Resour. S. Afr. No. 15, Dept. Agric. Dev., Pretoria.

SOIL SURVEY STAFF, 1987. Keys to soil taxonomy. SMSS techical monograph No. 6, Ithaca, New York.

THE NON-AFFILIATED SOIL ANALYSIS WORK COMMITTEE, 1990. Handbook of standard soil testing methods for advisory purposes. Soil Sci. Soc. S. Afr., Pretoria.

THOMAS, G.A., DALAL, R.C. & STANDLEY, J., 2007. No-till effects on organic matter, pH, cation exchange capacity, and nutrient distribution in a luvisol in the semiarid subtropics. *Soil Till*. *Res*. 94, 295-304.

TOTTMAN, D.R. & DAVIES, E.L.P., 1978. The effect of herbicides on the root system of wheat plants. *Ann. Appl. Bio*. 90, 93-99.

TU, C.M. & BOLLEN, W.B., 1968. Interaction between paraquat and microbes in soils. *Weed Res*. 8, 38-45.

VAN DEN BOSSCHE, A., DE BOLLE, S., DE NEVE, S. & HOFMAN, G., 2009. Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. *Soil Till*. *Res*. 103, 316-324.

VAN DER WAALS, J.H. & LAKER, M.C., 2008. Micronutrient deficiencies in crops in Africa with emphasis on Southern Africa. *In*: B.J. Alloway (ed). Micronutrient deficiencies in global crop production. Springer Science + Business Media B.V.

VENKATESH, M.S., MAJUMDAR, B. & KUMAR-KAILASH, P., 2003. Status of micronutrient cations under various land use systems of Meghalaya. *J. Ind. Soc. Soil Sci*. 51, 60-64.

VOGELER, I., ROGASIK, J., RUNDER, U., PANTEN, K. & SCHNUG, E., 2009. Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. *Soil Till*. *Res*. 103, 137-143.

WANG, N., XU, R.K. & LI, J.Y., 2010. Amelioration of an acid ultisol by agricultural by-products. *Land Degrad. Dev*. 10.1002/ldr.1025.

WEI, X., HAO, M., SHAO, M. & GALE, W.J., 2006. Changes in soil properties and the availability of soil micronutrients after 18 years of cropping and fertilization. *Soil Till. Res*. 91, 120-130.

WILTSHIRE, G.H. & DU PREEZ, C.C., 1993. Long-term effects of conservation practices on the nitrogen fertility of a soil cropped annually to wheat. *S. Afr. J. Plant Soil* 10, 70-76.

WRIGHT, A.L., HONS, R.M., LEMON, R.G., MCFARLAND, M.L. & NICHOLAS, R.L., 2007. Stratification of nutrients in soil for different tillage regimes and cotton rotations. *Soil Till. Res.* 96, 19-27.

XU, J.M., TANG, C. & CHEN, Z.L., 2006. Chemical composition controls residue decomposition in soils differing in initial pH. *Soil Biol. Biochem*. 38, 544-552.

XU, R.K. & COVENTRY, D.R., 2003. Soil pH changes associated with lupin and wheat plant materials incorporated in a red-brown earth soil. *Plant Soil.* 250, 113-119.

XU, R.K., COVENTRY, D.R., FARHOODI, A. & SCHULTZ, J.E., 2002. Soil acidification as influenced by crop rotations, stubble management, and application of nitrogenous fertiliser, Tearlee, South Australia. *Aust. J. Soil Res*. 40, 483-496.

YADVINDER-SINGH, BIJAY-SINGH & TIMSINA J., 2005. Crop residue management for nutrient cycling and improving soil productivity in rice based cropping systems in the tropics. *Adv*. *Agron*. 85, 269-407.

YUAN, J.H., XU, R.K., WANG, N. & LI, J.Y., 2011. Amendment of acid soils with crop residues and biochars. *Pedosphere*. 21, 302-308.