ORGANIC MATTER RESTORATION BY CONVERSION OF CULTIVATED LAND TO PERENNIAL PASTURE ON THREE AGRO-ECOSYSTEMS IN THE FREE STATE

by

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ABSTRACT

Understanding the process of organic matter degradation and restoration is important with regard to sustainable agricultural production on any agro-ecosystem, and of particular importance where degradation is relatively rapid, such as in the coarse textured savannah soils of the South African highveld. Organic matter degradation studies on such soils in three agro-ecosystems, Harrismith, Tweespruit and Kroonstad, have been undertaken by Du Toit *et al.* (1994), and Lobe *et al.* (2001). This study is concerned with organic matter restoration on the same agro-ecosystems, and is therefore complementary to the two earlier studies.

The objective was to investigate organic matter restoration at three depths, 0-50, 50-100 and 100-200 mm, on perennial pastures of different ages that had been established on lands which had been cultivated continuously for more than 20 years. Representative C and N values for degraded lands and virgin grasslands for the three agro-ecosystems were obtained from the studies of Du Toit *et al.* (1994) and Lobe *et al.* (2001), and used as reference values. To reduce within-site error samples were collected at six places, separated from each other by a few meters, at each site. At each of these places six subsamples of each layer were taken to make up the final sample. There were therefore 18 soil samples per site. A total of 28 sites, ranging in ages from 4 to 25 years, were identified and sampled on the three agro-ecosystems. All the samples were analyzed for C and N, and selected samples were analyzed to characterize the soil fertility levels and particle size distribution at each site.

Results showed a wide variation in the rate of organic matter restoration between sites in each of the agro-ecosystems, due mainly to differences in natural resource factors and management techniques. Most important of the latter was the application of N fertilizer. Where this was inadequate or absent, very low organic matter restoration rates were generally measured. An approximate threshold value of available N below which organic matter restoration is severely impaired appears to be about 15 mg kg^{-1}.

On pastures up to the age of 25 years most of the C and N storage has been in the 0-50 mm layer, a little in the 50-100 mm layer, and very little in the 100-200 mm layer. This observation accentuates the importance of the sampling depth in such studies. These results are in accordance with those of Potter *et al.* (1999). The mean C gains over all the sites in the three agro-ecosystems, excluding those with a N fertility level considered too low to initiate efficient C sequestration, is 0.56 Mg ha^{-1} yr^{-1} as compared to 0.8 Mg ha^{-1} yr^{-1} suggested by Bruce *et al.* (1999) for the United States of America and Canada. The relatively coarse texture of the Free State soils, and the lower aridity indices, may account for the difference.

An attempt was made by pooling the data for the three agro-ecosystems, and adopting a normalization procedure, to identify common C and N restoration curves with time. Although a definite upward trend is visible, large inter-site variation and the shortage of data points above 20 years results in relatively low correlation coefficients and the curves being unreliable at their top end. Further research to obtain data from very old pastures is recommended, as well as ecotope specific research on benchmark ecotopes to define in a reliable way the shape of the organic matter restoration curve.

Keywords: Coarse-textured soils, organic carbon, semi-arid agro-ecosystems, sustainable agriculture, total nitrogen

UITTREKSEL

Met betrekking tot volhoubare landbouproduksie is dit belangrik om die degradasie en restorasie prosesse van organiese materiaal op enige landbou-ekosisteem te verstaan. Waar degradasie relatief vinnig is, soos op die grof getekstuurde gronde van die Suid-Afrikaanse hoëveld, is dit van spesiale belang. Du Toit *et al.* (1994) en Lobe *et al.* (2001) het organiese materiaal degradasie op sulke gronde ondersoek in die drie landbou-ekosisteme Harrismith, Tweespruit en Kroonstad. Die studie wat hier beskryf word fokus op die restorasie van organiese materiaal op dieselfde landbou-ekosisteme, en dien dus as ondersteuning vir die twee vorige studies.

Die doel was om organiese materiaal restorasie op drie dieptes, 0-50, 50-100 en 100-200 mm, te ondersoek op meerjarige weidings van verskillende ouderdomme wat gevestig is op lande wat voorheen vir meer as 20 jaar onder bewerking was. Verwysingswaardes van C en N vir gedegradeerde lande en onversteurde grasveld op die drie landbou-ekosisteme is verkry uit die data van Du Toit *et al.* (1994) en Lobe *et al.* (2001). Ses monsterplekke is gebruik om die ruimtelike variasie by elke meetpunt te minimiseer. Die monsterplekke was 'n paar meter van mekaar geleë. Ses submonsters is by elke monsterplek geneem volgens 'n standaard prosedure, en dan gemeng om die finale monster op te maak. Daar was dus 18 finale grondmonsters per meetpunt. Die totale getal meetpunte op die drie landbou-ekosisteme was 28, met weidings tussen 4 en 25 jaar oud. Al die monsters is ontleed vir C en N, en geselekteerde monsters is ontleed om die grondvrugbaarheid en deeltjiegrootteverspreiding by elke meetpunt te karakteriseer.

Resultate wys 'n groot variasie in die tempo van organiese materiaal restorasie op die drie landbou-ekosisteme, hoofsaaklik weens verskille in natuurlike hulpbron faktore en bestuurspraktyke. Van laasgenoemde is die toediening van stikstofkunsmis die belangrikste. Waar dit te min was het metings 'n baie lae tempo van organiese materiaal restorasie gewys. 'n Benaderde drumpelwaarde van beskikbare N waaronder organiese materiaal restorasie ernstig beperk word, is blykbaar naastenby 15 mg kg^{-1}.

Op weidings tot op die ouderdom van 25 jaar is die meeste C en N in die 0-50 mm laag gestoor, min in die 50-100 mm laag, en baie min in die 100-200 mm laag. Dit beklemtoon die belangrikheid van die diepte van monsterneming in studies van hierdie aard. Hierdie resultate stem ooreen met die van Potter *et al.* (1999). Die gemiddelde C toename oor al die meetpunte op die drie landbou-ekosisteme, met dié met 'n gebrek aan N uitgesluit, is 0.56 Mg ha^{-1} jr^{-1} in vergelyking met die waarde van 0.8 Mg ha^{-1} jr^{-1} wat deur Bruce *et al.* (1999) vir die Verenigde State van Amerika en Kanada voorgestel word. Die rede vir die verskil is heelwaarskynlik die laer kleiinhoude en ariditeitsindekse van die Vrystaatse landbou-ekosisteme.

Deur die data van die drie landbou-ekosisteme te poel, en met die gebruik van 'n prosedure van normalisering, is 'n poging aangewend om 'n enkel restorasiekurwe vir C en vir N te identifiseer. Alhoewel daar 'n duidelike opwaartse neiging is, is die kurwes bokant om en by 15 jaar onbetroubaar weens groot variasie tussen meetpunte van dieselfde ouderdom, en 'n gebrek aan gegewens vir weidings van meer as 20 jaar oud. Korrelasiekoeffisiente is dus relatief laag. Addisionele navorsing moet gedoen word om inligting te kry oor weidings tussen 15 en 100 jaar oud, asook op sleutel-ekotope om die vorm van die restorasiekurwe meer betroubaar te definieer.

Sleutelwoorde: grof getekstuurde gronde, organiese koolstof, semi-ariede landbou-ekosisteme, totale stikstof, volhoubare landbou

DECLARATION

I declare that the dissertation hereby submitted by me for the Magister Scientiae Agriculturae degree at the University of the Free State is my own independent work and hasn't previously been submitted by me to any other university or faculties. I further concede copyright for the dissertation in favour of the University of the Free State.

Signed ______________________

Tilahun Chibsa Birru

DEDICATION

To God to enable me to pursue my study; to my parents, Mr Chibsa Birru and Mrs. Alemi Soboqa, for their effort to bring me up; to my wife, Yeshi Tamene and my daughter, Meti; to my brothers and sisters as well as to my promoters for encouraging me to work hard to finish my study.

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LIST OF SYMBOLS AND ABBREVIATIONS

AI	=	Aridity index which is the ratio of rainfall to class A pan evaporation for a specific period
AS	=	Acid saturation which is the ratio of exchangeable acid cations (H and Al) to CEC
Av	=	Avalon form soil
BS	=	Base saturation which is the ratio of exchangeable basic cations (Ca, Mg, K and Na) to CEC
C	=	Organic carbon
C_e	=	Equilibrium concentration of C after more than 20 yrs of cultivation
C_0	=	Concentration of C in virgin soil.
C_p	=	Concentration of C in the restored pasture site
CEC	=	Cation exchange capacity
CRP	=	Carbon restoration percentage defined as $(C_p\text{-}C_e)*100/C_e$
DL	=	Degradation loss defined as $(C_0\text{-}C_e)$ for C and $(N_0\text{-}N_e)$ for N in absolute terms and as $(C_0\text{-}C_e)*100/C_0$ for C and $(N_0\text{-}N_e)*100/N_0$ for N in relative terms
E_0	=	Class A pan evaporation (mm)
GSD	=	Grass sward density
HS	=	Harrismith
KR	=	Kroonstad
LSD	=	Least significance difference
MAR	=	Mean annual rainfall
MARP	=	Mean annual rainfall during the period under pasture
N	=	Total nitrogen
N_e	=	Equilibrium concentration of N after more than 20 yrs of cultivation
N_0	=	Concentration of N in virgin soil.
N_p	=	Concentration of N in the restored pasture site
NRP	=	Nitrogen restoration percentage defined as $(N_p\text{-}N_e)*100/N_e$

PCP	=	Previous cultivation period
R	=	Restoration percentage defined as $(C_p-C_e)*100/(C_0-C_e)$ for C or $(N_p-N_e)*100/(N_0-N_e)$ for N
RG	=	Restoration gain (C_p-C_e) for C or (N_p-N_e) for N
RP	=	Restoration period
R % yr^{-1}	=	Restoration percentage per year
SD	=	Soil depth
SOM	=	Soil organic matter
Ta	=	Mean annual temperature
Tm	=	Mean monthly temperature, viz. (Tmax + Tmin)/2
Tmax	=	Mean daily maximum temperature for each month
Tmin	=	Mean daily minimum temperature for each month
TMU	=	Terrain morphological unit
TW	=	Tweespruit
We	=	Westleigh form soil

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

In this study on organic matter restoration by conversion of cultivated land to perennial pasture on three agro-ecosystems in the Free State two terms are used which may cause uncertainties. For the purpose of clarity it is necessary to define the meaning of these two terms, viz. cultivated land and agro-ecosystem.

- Cultivated land is land that has been under continuous cultivation for more than twenty years.
- Agro-ecosystem is an area of land on which the climate, topography and soil, the three natural resource factors that influence agricultural potential, are reasonably similar.

An agro-ecosystem can also be described as being similar to an ecotope (MacVicar, Scotney, Skinner, Niehaus & Loubser, 1974), or a group of very similar ecotopes. The agro-ecosystems referred to in the title were all situated in the Free State Province of South Africa and were all similar in a number of respects. Plinthosols (FAO, 1998), or Plinthustalfs (Soil Survey Staff, 1998), including the Avalon and Westleigh forms as described in "Soil Classification: A Taxonomic System for South Africa" (Soil Classification Working Group, 1991), were the main soils in this study.

Soils supply water and nutrients for crop growth. The productivity of cropland is therefore determined to a large extent by the soil's ability to supply the necessary water and nutrients. Both of these capacities are strongly influenced by the organic matter content of soil. According to Smith & Elliot (1990), soil organic matter (SOM) is a heterogeneous mixture of living, dead and decomposing organic compounds and inorganic compounds, containing various amounts of carbon, hydrogen, oxygen, nitrogen, phosphorus, sulfur, and traces of other elements.

According to Stevenson (1982), as quoted by Smith & Elliot (1990), SOM plays an important role in soil physical properties, viz.: its dark color facilitates soil warming; it improves water retention capacity and holds up to 20 times its own mass of water; it prevents drying and shrinking of soil; in combination with clay minerals it forms stable porous aggregates thereby increasing porosity, with all the associated benefits of improved gas exchange and increased permeability and water retention. With regard to the influence of SOM on the supply of nutrients, MacCarthy, Clapp, Malcolm & Bloom (1990) indicated that SOM is valuable because it provides slow release of N, P and S; contributes to the cation exchange capacity (CEC); has a plant growth stimulating effect via enzymes and hormones; and impairs the effects of toxic and non-ionic compounds by removing them from the soil solution. Smith & Elliot (1990) also found for example that 95% of N, 40% of P, and 90% of S used by plants often comes from SOM. Furthermore the following beneficial effects of SOM are listed by Stevenson (1982), as quoted by Smith & Elliot (1990), viz. by chelation it forms stable complexes with copper, manganese and zinc and other polyvalent micronutrients, thereby enhancing their availability to plants; it impairs the leaching of nutrient cations via its contribution to CEC (from 20-70% of the CEC of the soil may be contributed by SOM); it affects the bio-activity, persistence and biodegradability of pesticides, thereby modifying the application rate of pesticides necessary for effective control.

In the semi-arid region of the Free State Province of South Africa Plinthosols or Plinthustalfs are among the most important soils for agricultural production. They cover a large fraction of the arable land, as is indicated on the map by Beukes, Bennie & Hensley (1999). Their fertility level is of great importance for soil productivity and it is generally known that these soils tend to be low in organic matter. Du Preez & Du Toit (1995) have also suggested that depletion of N fertility in these cultivated soils might result in unsustainable crop production.

Therefore, to sustain the productive capacity of land it is important to maintain or restore organic matter through reversion of the cultivated land to pasture. To do this some South African commercial farmers manage their land by periodically converting cultivated lands to pastures using different management systems. Restoration requires time and its effectiveness depends on the management that the farmers apply. Generally, well-managed pasture may require relatively little time to restore the fertility level, but badly managed pasture may require a longer period. Restoring the fertility level and studying the factors controlling the organic matter levels in soils is therefore important for sustainable agricultural production, especially in the semi-arid and sub-humid regions of South Africa. This research attempts to address this need.

1.2 HYPOTHESIS

The rate of SOM restoration in cultivated land reverted to pasture depends on the prevailing climate, topography and soil, and the management practices adopted.

1.3 OBJECTIVES

1. To describe organic matter restoration on three agro-ecosystems and attempt to interpret the results in terms of climate, topography, soil, vegetation and management.
2. To investigate the degree of organic matter restoration at three depth intervals, viz. 0-50, 50-100 and 100-200 mm, using virgin soils and those which have been under cultivation for more than 20 years as reference.
3. To compare organic matter restoration on the three selected agro-ecosystems.
4. To relate organic matter restoration for each agro-ecosystem to the previously determined degradation curves, on the same agro-ecosystems, by Du Toit, Du Preez, Hensley & Bennie (1994) and Lobe, Amelung & Du Preez (2001).
5. To attempt to integrate the results of the three agro-ecosystems to describe a common restoration pattern.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The focus of this literature review will be restricted to the degradation and restoration of SOM on cultivated lands from different agro-ecosystems in the world. Firstly, SOM degradation on cultivated lands will be discussed with special emphasis to the three South African agro-ecosystems included in this study. However, some attention will be given also to the degradation of SOM on cultivated lands from agro-ecosystems in Canada and Nigeria. Secondly, a discussion of the restoration of SOM on cultivated lands converted to perennial pasture will follow. Information of this nature does not exist for the three South African agro-ecosystems included in this study. Therefore the emphasis will be on another South African agro-ecosystem and agro-ecosystems from the United States of America and Australia.

In most studies either organic C and/or total N were used as indices of SOM degradation and restoration. Therefore when referring to C and/or N it is in this context except if otherwise indicated.

2.2 SOIL ORGANIC MATTER DEGRADATION ON CULTIVATED LANDS

2.2.1 Savanna soils in the Free State, South Africa

Losses of C and N with prolonged arable cropping from coarse textured savannah soils of the South African highveld were studied by Du Toit *et al.* (1994) and Lobe *et al.* (2001). Both studies included the three agro-ecosystems which will here be named according to the districts in which they occur, i.e. Harrismith, Tweespruit, and Kroonstad as displayed in Figure 2.1.

Essential natural resource information on the three agro-ecosystems is given in Table 2.1. The data shows that although all three agro-ecosystems are on the South African highveld, there is a significant difference between their climates on an annual basis. The altitudes decrease in the order Harrismith, Tweespruit, Kroonstad and therefore, as is to be expected, the temperatures increase in the same order. Harrismith is clearly by far the coolest and wettest agro-ecosystem agro-ecosystem of the three, with an aridity index of 0.36 compared to 0.28 for Kroonstad and 0.27 for Tweespruit. Although the rainfall at Kroonstad is higher than that at Tweespruit, the similarity of the aridity index values is presumably due to a slightly lower temperature at Tweespruit and a slightly lower evaporative demand.

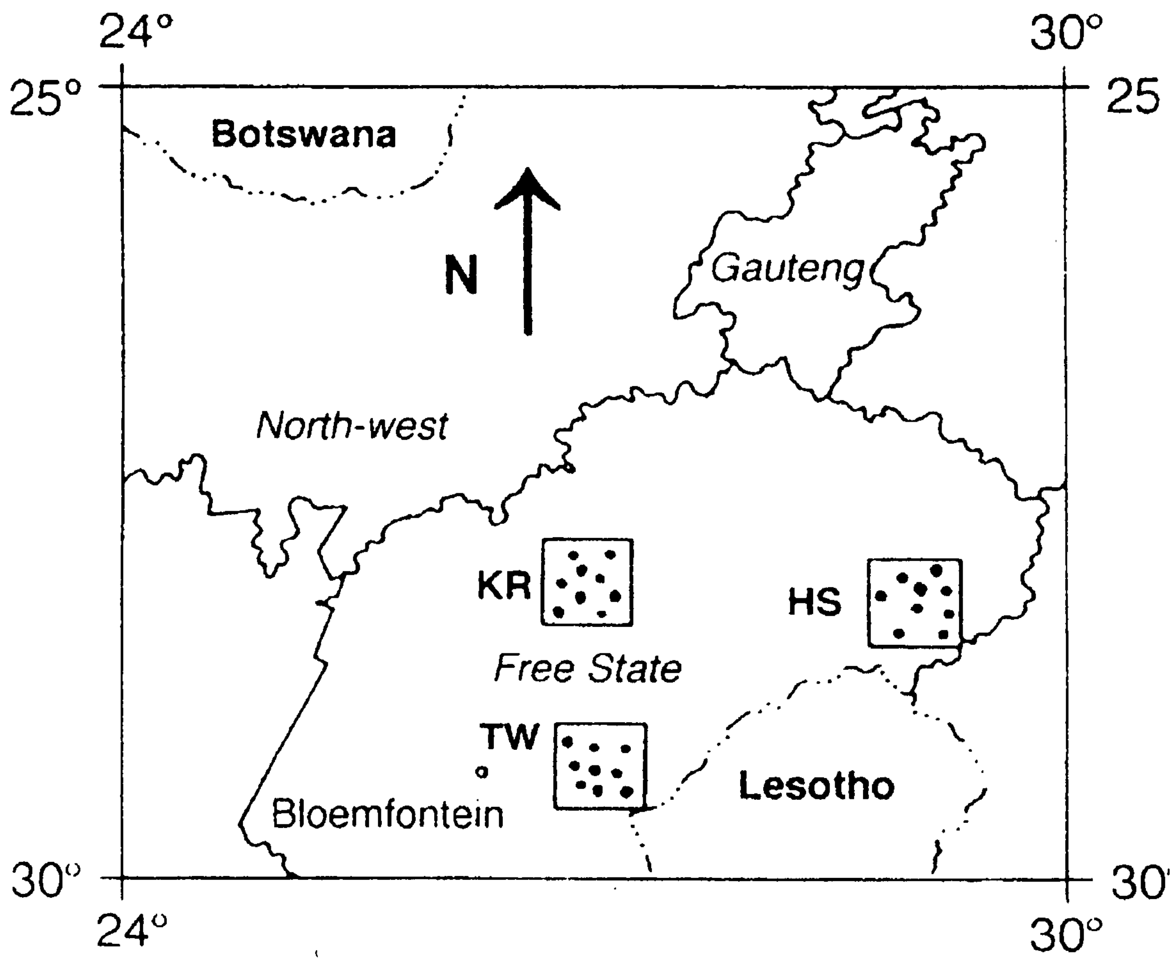


Figure 2.1 The location of the sampling sites at the three agro-ecosystems in the Free State Province of South Africa (after Lobe *et al.*, 2001). Meaning of abbreviations as defined in the beginning of the dissertation.

As already mentioned the Avalon and Westleigh soil forms (Soil Classification Working Group, 1991) are Plinthosols (FAO, 1998), or Plinthustalfs (Soil Survey Staff, 1998). However the importance of clay content with regard to SOM degradation has been demonstrated by a number of workers (Birch & Friend, 1956; Jones, 1973; Du Toit *et al.*, 1994; Lobe *et al.*, 2001). The clay percentage in the agro-ecosystems described in Table 2.1 varied as follows for Harrismith: 9-19%, with one site not included having 22%; for Tweespruit: 10-21%, with the majority falling below 16%; and for Kroonstad: 6-15%, with the majority falling above 10% (Du Toit *et al.*, 1994; Lobe *et al.*, 2001). In Table 2.2 the C and N contents after different periods of cultivation on the three agro-ecosystems are presented.

Table 2.1 Essential natural resource information about the three agro-ecosystems studied by Du Toit *et al.* (1994) and Lobe *et al.* (2001). Meaning of abbreviations as defined in the beginning of the dissertation.

Agro-ecosystem	Altitude (m)	Climatic data			Soils	Clay(%)		Sampling depth (mm)
		MAR (mm)	AI	Ta (°C)		Du Toit	Lobe	
HS	± 1800	624	0.36	13.8	Mainly Av	9 - 16	13 - 19	0 - 200
TW	± 1600	544	0.27	14.8	Mainly We	12 - 21	10 - 16	0 - 200
KR	± 1400	566	0.28	16.6	Mainly Av	6 - 11	10 - 15	0 - 200

The C and N degradation associated with different periods of cultivation can be effectively described by an exponential model, which assumes that SOM reaches an equilibrium concentration with time (Du Toit *et al.*, 1994; Lobe *et al.*, 2001). The relevant equation for C is:

$$C_t = C_e + (C_0 - C_e)\exp(-C_r t) \qquad 2.1$$

Where C_t = concentration of C at time t; C_e = equilibrium concentration of C; C_0 = the initial concentration of C at 0 years of cultivation; and C_r = rate constant (yr^{-1}).

In the case of N the relevant equation is:

$$N_t = N_e + (N_0 - N_e)\exp(-N_r t) \qquad 2.2$$

where N_t = concentration of N at time t; N_e = equilibrium concentration of N; N_0 = the initial concentration of N at 0 years of cultivation; and N_r = rate constant (yr^{-1}).

Table 2.2 The C and N concentrations in the 0-200 mm layer of the three agro-ecosystems studied by Du Toit *et al.* (1994) and Lobe *et al.* (2001). Meaning of abbreviations as defined in the beginning of the dissertation

Harrismith			Tweespruit			Kroonstad		
*Cultivation period (yrs)	C ($g\ kg^{-1}$)	N ($mg\ kg^{-1}$)	Cultivation period (yrs)	C ($g\ kg^{-1}$)	N ($mg\ kg^{-1}$)	Cultivation period (yrs)	C ($g\ kg^{-1}$)	N ($mg\ kg^{-1}$)
Only data of Du Toit *et al.* (1994)								
0	17.6	1274	0	10.5	1058	0	5.6	557
8	11.6	908	8	7.1	724	6	3.9	414
11	9.1	750	27	4.4	566	9	2.1	223
20	8.9	742	45	2.6	335	15	3.4	361
30	5.7	482	85	4.2	526	30	3.9	410
54	6.5	579				90	3.2	383
59	7.0	606						
Only data of Lobe *et al.* (1994)								
0	20.6	1600	0	11.7	1120	0	8	851
3.5	11.0	1040	2	11.4	1140	2.5	5.3	610
8	13.5	1110	8.5	7.1	730	7.5	4.3	530
10	10.6	940	12	6.4	670	12	3.9	490
20	7.8	730	22	5.8	580	20	4.0	490
30	9.3	880	32	5.3	610	30	2.9	460
45	8.6	790	40	4.4	520	40	3.4	450
68	6.8	660	60	5.3	600	57	2.9	430
90	6.3	660	90	4.3	540	98	2.7	400
Combined data of Du Toit *et al.* (1994) and Lobe *et al.* (2001)								
0	19.1	1437	0	11.1	1089	0	6.8	704
3.5	11.0	1040	2	11.4	1140	2.5	5.3	610
8	13.5	1110	8	7.1	724	6	3.9	414
8	11.6	908	8.5	7.1	730	7.5	4.3	530
10	10.6	940	12	6.4	670	9	2.1	223
11	9.1	750	22	5.8	580	12	3.9	490
20	7.8	730	27	4.4	566	15	3.4	361
20	8.9	742	32	5.3	610	20	4.0	490
30	9.3	880	40	4.4	520	30	3.9	410
30	5.7	482	45	2.6	335	30	2.9	460
45	8.6	790	60	5.3	600	40	3.4	450
54	6.5	579	85	4.2	526	57	2.9	430
59	7.0	606	90	4.3	540	90	3.2	383
68	6.8	660				98	2.7	400
90	6.3	660						

*Cultivation period of 0 yrs represents virgin soil.

The three data sets in Table 2.2 were fitted to Equations 2.1 and 2.2 using the Mathlab programme to obtain representative degradation curves for C and N with corresponding equation parameters C_r, N_r, C_e and N_e. These degradation curves of C and N are shown for each of the three agro-ecosystems: the first three pairs of curves (Figures 2.2 and 2.3) are for Du Toit *et al.* (1994); the next three pairs (Figures 2.4 and 2.5) for Lobe *et al.* (2001); and the last three pairs (Figures 2.6 and 2.7) for the combined data of Du Toit *et al.* (1994) and Lobe *et al.* (2001). The calculated values of the parameters for the degradation equations are given in Table 2.3.

The overall similarity of the degradation patterns for C and N obtained by Du Toit *et al.* (1994) and Lobe *et al.* (2001) provides strong evidence for the reliability of their data. Because of this similarity it is expedient to discuss only the more reliable combined data. In the virgin soil the Harrismith agro-ecosystem is shown to have the highest C and N content (C_0 and N_0 respectively), Kroonstad the lowest, and Tweespruit intermediate between the two. Coarser soil textures and lower aridity indices at Tweespruit and Kroonstad are probably factors which contribute to this order. The equilibrium C and N concentrations (C_e and N_e respectively) in the three agro-ecosystems decrease in the same order. Expressing the degradation loss of C in percentage as DL = $[(C_0 - C_e)*100 / C_0]$ yields the following results for the three agro-ecosystems: 60% for Harrismith after 35 years of cultivation, 63% for Tweespruit after 44 years of cultivation and 52% for Kroonstad after 14 years of cultivation. Similarly, the degradation loss of N in percentage as DL = $[(N_0 - N_e)*100]/ N_0$ yields the following results for the three agro-ecosystems: 53% for Harrismith after 34 years of cultivation, 55% for Tweespruit after 35 years of cultivation, and 42% for Kroonstad after 10 years of cultivation. The overall similarity between Harrismith and Tweespruit is repeated in the similarity of their degradation rate indices C_r and N_r. The influence of the cooler, moister climate of Harrismith is probably balanced by the moister A horizon of the Westleigh form soils at Tweespruit caused by the soft plinthic B horizon generally being at a depth of about 250 mm compared to 600 mm in the Avalon soils of Harrismith. Although the C degradation loss at Kroonstad is slightly lower than at Harrismith and Tweespruit the time to reach equilibrium is less than one third of the other two, resulting in a much higher C_r value of 0.28 for Kroonstad compared to 0.12 for Harrismith and 0.10 for Tweespruit. The main controlling

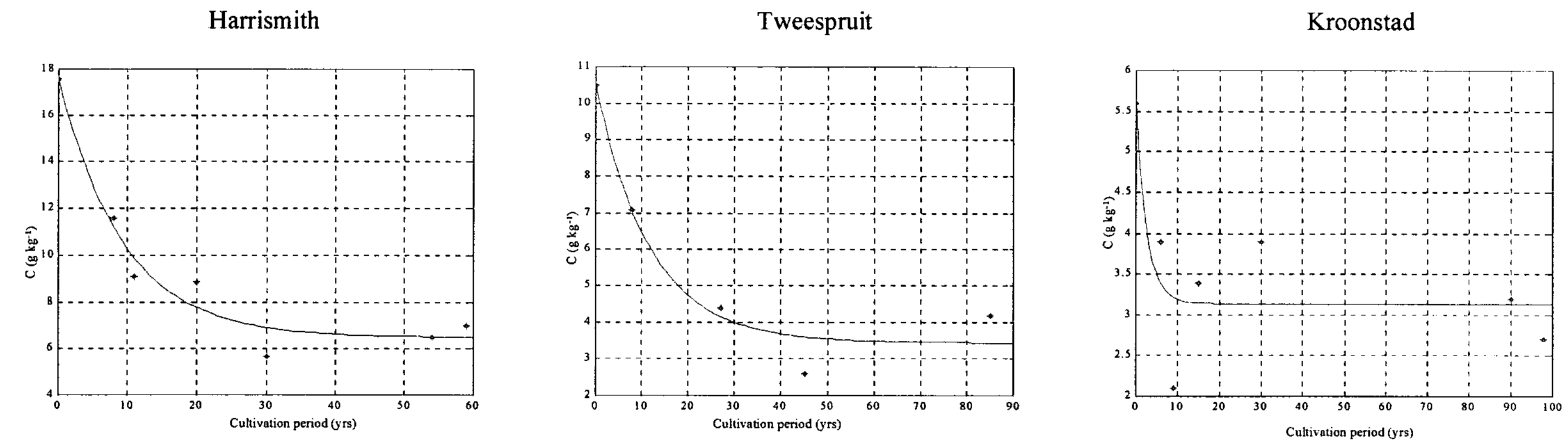


Figure 2.2 Degradation curves for carbon on the three agro-ecosystems (data of Du Toit *et al.*,1994).

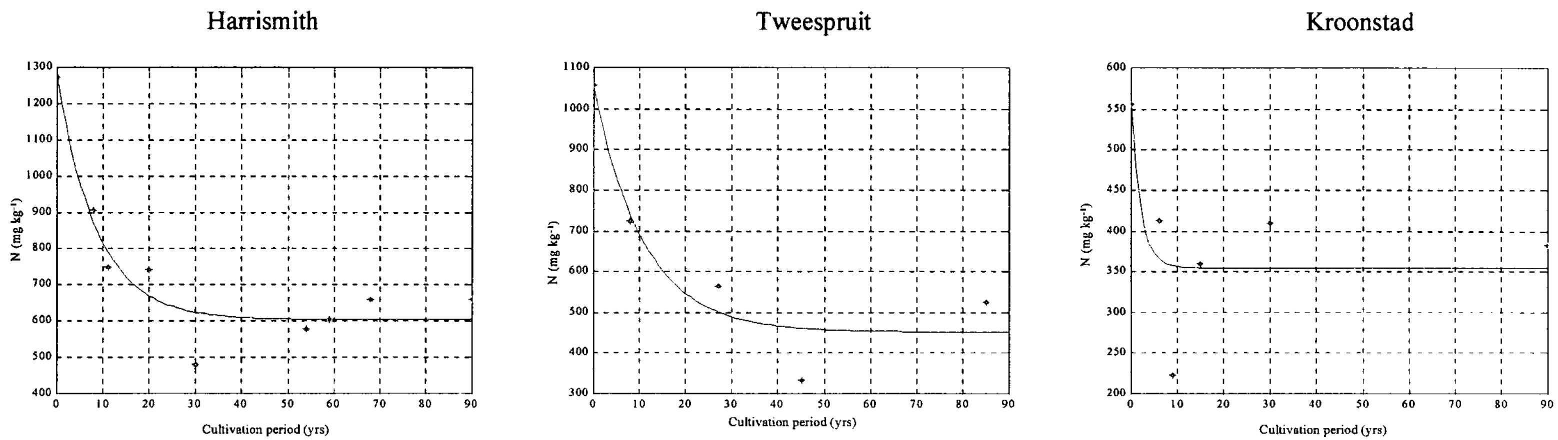


Figure 2.3 Degradation curves for nitrogen on the three agro-ecosystems (data of Du Toit *et al.*, 1994).

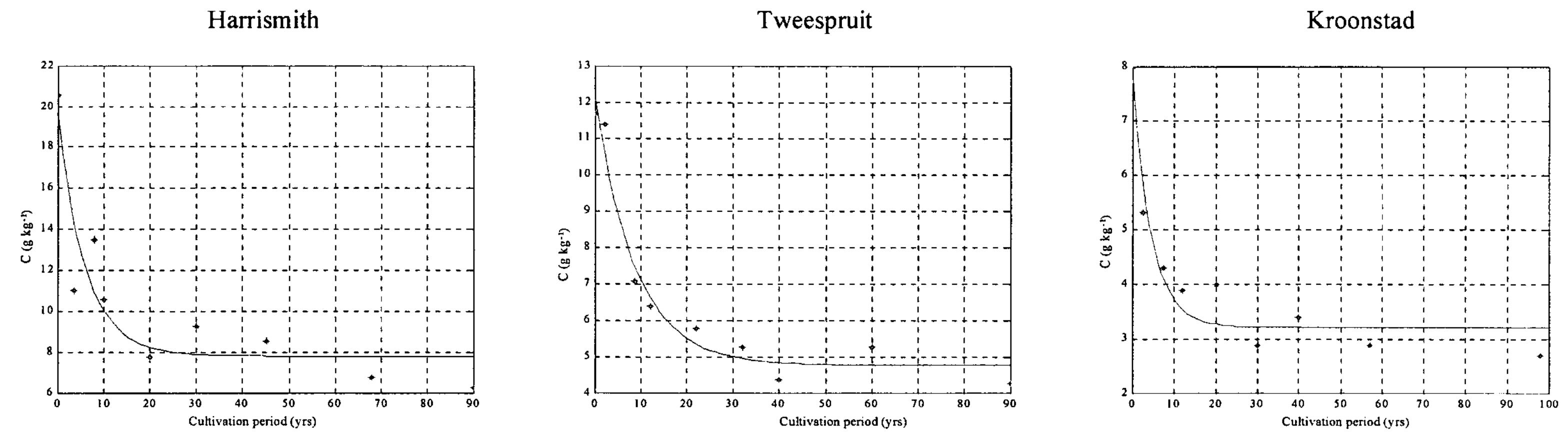


Figure 2.4 Degradation curves for carbon on the three agro-ecosystems (data of Lobe *et al.*, 2001).

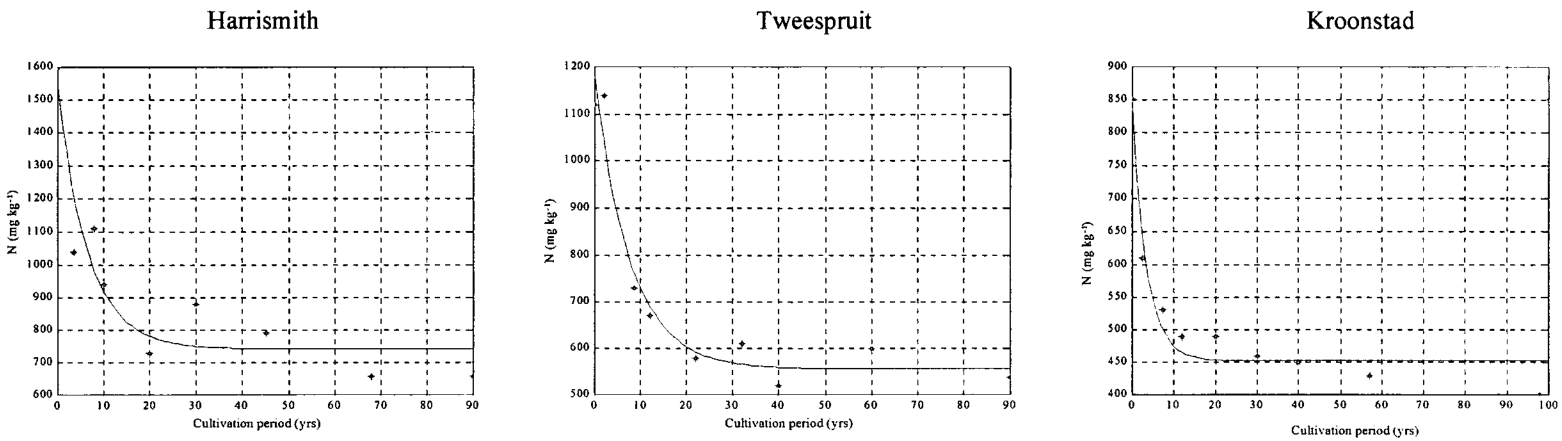


Figure 2.5 Degradation curves for nitrogen on the three agro-ecosystems (data of Lobe *et al.*, 2001).

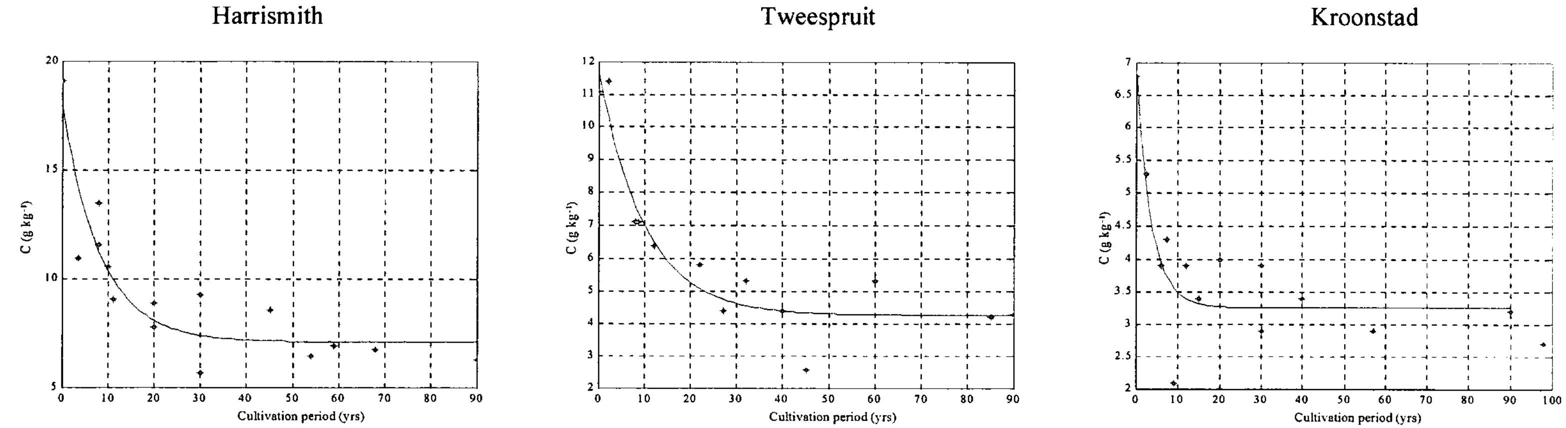


Figure 2.6 Degradation curves for carbon on the three agro-ecosystems (combined data of Du Toit *et al.*, 1994 and Lobe *et al.*, 2001).

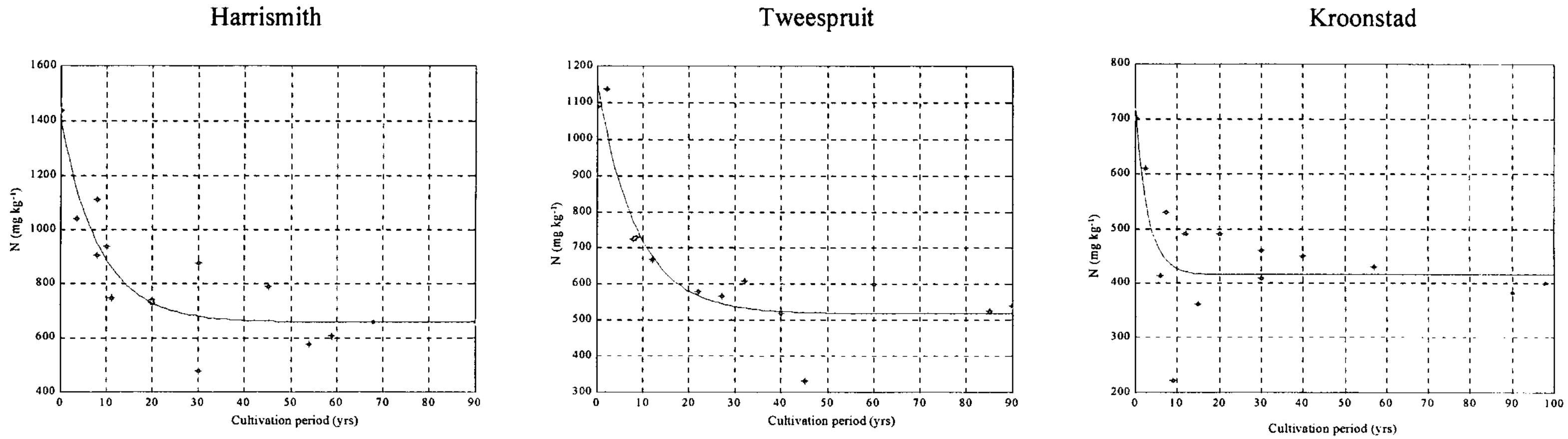


Figure 2.7 Degradation curves for nitrogen on the three agro-ecosystems (combined data of Du Toit *et al.*, 1994 and Lobe *et al.*, 2001).

Table 2.3 Calculated parameters of Equations 2.1 and 2.2 for the three agro-ecosystems obtained by using the data in Table 2.2. Meaning of abbreviations as defined in the beginning of the dissertation.

Agro-ecosystem	C_0 (g kg^{-1})	N_0 (mg kg^{-1})	C_e (g kg^{-1})	N_e (mg kg^{-1})	C_r (yr^{-1})	N_r (yr^{-1})	R^2		Period to reach equilibrium (yr)	
							C	N	C	N
Only data of Du Toit *et al.* (1994)										
Harrismith	17.6	1277	6.5	564	0.1079	0.0001	0.61	0.63	41	40
Tweespruit	10.5	1054	3.5	452	0.0855	0.0001	0.62	0.60	54	45
Kroonstad	5.6	558	3.3	355	0.4383	0.4816	0.16	0.15	8	6
Only data of Lobe *et al.* (2001)										
Harrismith	19.5	1541	7.8	742	0.1680	0.0002	0.41	0.44	25	26
Tweespruit	12.1	1181	4.8	557	0.1153	0.0001	0.51	0.48	37	31
Kroonstad	7.8	840	3.2	453	0.2215	0.2844	0.32	0.28	19	13
Combined data of Du Toit *et al.* (1994) and Lobe *et al.* (2001)										
Harrismith	17.9	1400	7.1	659	0.1209	0.0001	0.50	0.51	35	34
Tweespruit	11.7	1155	4.3	518	0.1006	0.0001	0.53	0.49	44	35
Kroonstad	6.9	722	3.3	416	0.2769	0.3298	0.21	0.18	14	10

factor is probably the higher mean annual temperature of 16.7 °C at Kroonstad as compared to 14.8 °C for Tweespruit and 13.8 °C for Harrismith. The higher temperature would promote C and N degradation. The reason for the very high N_r value for Kroonstad compared to that of Harrismith and Tweespruit is not clear.

The degradation losses for C in percentage for these three agro-ecosystems caused by continuous cultivation are somewhat similar to those reported by Theron (1955) for a red loam soil on the experimental farm of the University of Pretoria. His results show that under continuous maize the organic matter lost, compared to virgin soil, was 29 and 38% after 10 and 15 years of cultivation, respectively. The higher aridity index value and clay content of that agro-ecosystem can be expected to have buffered the decline of C to some extent compared to Kroonstad for example.

2.2.2 Prairie soils in Saskatchewan, Canada

The effects of cultivation on the C and N content in the Saskatchewan Province of Canada was studied by Tiessen, Stewart & Bettany (1982). Cultivated and adjacent uncultivated lands were sampled by them on three agro-ecosystems, viz. Blaine Lake, Bradwell and Sutherland. The depth of cultivation in Saskatchewan is usually only 0-100 mm. Some results of Tiessen *et al.* (1982) are presented in Table 2.4.

The following are some of the important observations and conclusions that can be drawn from the experimental results: the virgin prairie soils have high C contents (3.2 to 4.8%) in this cold climate, i.e. humic in the South African soil classification system; C degradation seems to continue after 60 years of continuous cultivation in the fine textured soils (silt loam to clay), with about 33% having been lost after 60-70 years of cultivation; C degradation in the coarse textured soil (sandy loam) is much more rapid than in the fine textured soils, i.e. 46% lost after 65 years of cultivation. A confusing factor is however the variation in sampling depth, especially in view of the fact that the cultivation depth in the area is stated to be 0-100 mm. A better sampling depth throughout would therefore have been 0-100 mm. The C losses in the fine textured soils seem to be of a similar order to those reported by Potter, Torbert, Johnson

& Tischler (1999) for vertic prairie soils with high C contents in Texas, in the United States of America i.e. about 50% loss in the top 150 mm after about 100 years of cultivation.

Table 2.4 Degradation of C after different periods of cultivation on three prairie agro-ecosystems with humic soils in the Saskatchewan Province of Canada (after Tiessen *et al.*, 1982). Meaning of abbreviations as defined in the beginning of the dissertation.

Agro-ecosystem	Soils		Degradation of C after different cultivation periods			
Blaine Lake	Chernozemic silt loam		0 yrs	4 yrs	60 yrs	90 yrs
		C (g kg^{-1})	47.9	49.0	32.8	20.0
		DL (%)	0	-2	32	58
		SD (mm)	108	133	145	90
Bradwell	Chernozemic sandy loam		0 yrs	65 yrs		
		C (g kg^{-1})	32.2	17.4		
		DL (%)	0	46		
		SD (mm)	148	138		
Sutherland	Vertic clay		0 yrs	70 yrs		
		C (g kg^{-1})	37.7	23.7		
		DL (%)	0	37		
		SD (mm)	180	180		

2.2.3 Tropical soils in South Western Nigeria

The effect of continuous cultivation on a tropical Ultisol was studied in South Western Nigeria by Obi (1989) and some of his results are presented in Table 2.5. This agro-ecosystem has a high mean temperature and a moist soil water regime.

Table 2.5 Degradation of C in the 0-150 mm layer of a well drained loamy sand Oxic-Tropodolf in South Western Nigeria after different periods of continuous cultivation (after Obi, 1989). Meaning of abbreviations as defined in the beginning of the dissertation.

	Degradation of C after different cultivation periods			
	0 yrs	5 yrs	10 yrs	15 yrs
C (g kg^{-1})	18.0	8.7	7.1	6.5
DL (%)	0	52	61	64

The results in Table 2.5 are averages from a fertilizer experiment with 13 N treatments consisting of different kinds of fertilizers applied at levels ranging from 69 to 276 kg N ha^{-1} yr^{-1}. A basal application of P and K was also made. It was found that the different N treatments had no significant influence on C degradation. The degradation of C is shown to be rapid in this coarse textured soil under tropical conditions. The percentage loss after only 15 years is similar to that in the Blaine Lake agro-ecosystem with a silt loam soil in Saskatchewan, Canada after 90 years of cultivation (Tiessen *et al.* 1982), and that on a vertic clay in Texas, United States of America after more than 100 years of cultivation (Potter *et al.*, 1999). These results accentuate the important role of climate and soil texture in C degradation under continuous cultivation.

2.3 SOIL ORGANIC MATTER RESTORATON ON CULTIVATED LANDS

2.3.1 Vertic clay soils in Texas, United States of America

The storage of C after long-term pasture establishment on degraded soils was studied by Potter *et al.* (1999). Three agro-ecosystems namely Temple, Burlesten and Riesel approximately 75 km apart in Texas, United States of America were included. They have a mean annual rainfall of 878 to 900 mm, and a mean annual temperature of 19.5°C. The soils at all sites were Vertisols, viz. Houston black clays. Summarized results of the investigation are presented in Table 2.6.

Table 2.6 Restoration of C in three similar agro-ecosystems in Texas, United States of America with degraded vertic clay soils placed under perennial pasture for different periods (after Potter *et al.*, 1999). Meaning of abbreviations as defined in the beginning of the dissertation.

Agro-ecosystem	SD (mm)	C_0 (g kg $^{-1}$)	Degraded soil after 100 years cultivation			Restoration by perennial pasture			RP (yrs)
			C_e (g kg $^{-1}$)	DL (g kg $^{-1}$)	DL (%)	C_p (g kg $^{-1}$)	RG (g kg $^{-1}$)	R (%)	
Temple	0-50	59.5	18.0	41.5	69.7	22.2	4.2	10.1	6
	50-100	30.8	17.2	13.6	44.2	17.3	0.1	0.7	
	100-150	25.6	17.2	8.4	32.8	15.7	0.0	0.0	
	150-200	22.8	15.6	7.2	31.6	14.3	0.0	0.0	
Burlesten	0-50	44.4	15.3	29.1	65.5	24.5	9.2	31.6	26
	50-100	31.4	15.4	16.0	51.0	17.3	1.9	11.9	
	100-150	27.4	12.5	14.9	54.4	15.2	2.7	18.1	
	150-200	23.6	12.5	11.1	47.0	14.8	2.3	20.7	
Riesel	0-50	54.9	18.8	36.1	65.8	38.6	19.8	54.8	60
	50-100	36.5	18.5	18.0	49.3	24.5	6.0	33.3	
	100-150	32.6	15.8	16.8	51.5	21.7	5.9	35.1	
	150-200	28.3	15.1	13.2	46.6	19.7	4.6	34.8	

The results show that after more than 100 years of cultivation 65-70% of C was lost in the 0-50 mm soil layer which is the most sensitive, and 33-50% in the deeper layers. The restoration under pasture in the sensitive 0-50 mm layer was 10% after 6 years, 32% after 26 years, and 55% after 60 years. The results also indicate that under the prevailing conditions the rate of restoration was slowing down with time, and that it may take a restoration period of about twice the length of the degradation period to restore the organic matter to what it was in the virgin soil.

The restoration of N, the data for which are not included, followed similar trends to those of C restoration in the three agro-ecosystems.

2.3.2 Red earth soils in New South Wales, Australia

Oxidizable organic carbon fractions and soil quality changes under different pasture leys were studied by Chan, Bowman & Oates (2001). Their experiment was located at latitude 31°34'S, longitude 147°12'E in western New South Wales, Australia. This region has a semi-arid climate with a mean annual rainfall of 431 mm and mean annual temperature of 18.8°C. A red earth soil (Oxic Paleustalf) with 32% clay dominates the experimental site. It had been under continuous cropping for 50 years, mainly with wheat using repeated tillage, stubble burning, and fallowing production techniques. The average yield was very low, around 1 ton ha^{-1} yr^{-1}. Pasture ley treatments included lucerne and *Eragrostis curvula.* The vegetation was cut for hay four times a year, half of the material being returned to the soil to simulate a moderate level of grazing. A fallow treatment with no vegetation served as control.

Soil samples were collected by Chan *et al.* (2001) from the 0-100 mm layer to determine C restoration. The organic C was determined by a dry combustion method and also by the Walkley-Black procedure. Calculations showed that the results of the Walkley-Black procedure were generally about 77% of the dry combustion method. In order to make the results of Chan *et al.* (2001) comparable to the more common Walkley-Black results reported by the other researchers, all the organic C results were multiplied by 0.77. These results are presented in Table 2.7.

As can clearly be seen from Table 2.7 long-term cultivation had greatly reduced the C and N contents, the percentage loss for both being 63%. Restoration of C under *Eragrostis curvula* and lucerne after 4 years was shown to be 12.1 and 13.3%, respectively. However, the N restoration by lucerne was more than double that which occurred under *Eragrostis curvula,* viz. 16.5 and 6.9%, respectively. If the restoration curve is linear then C can be expected to return back to its content in the virgin soil after $\pm$ 32 years under pasture under the prevailing conditions. This is however unlikely as other research workers (Potter *et al.,* 1999; Bruce *et al.*, 1999) consider that the rate of C restoration will almost certainly decrease with time.

Table 2.7 The C and N contents in the 0-100 mm layer of a red clay loam soil in New South Wales, Australia after a four year period under two kinds of pasture (After Chan *et al.*, 2001). Meaning of abbreviations as defined in the beginning of the dissertation.

Constituent	C_0	Degraded soil			After four years under pasture					
					Eragrostis curvula			Lucerne		
		C_e or N_e	DL	DL(%)	C_p or N_p	RG	R(%)	C_p or N_p	RG	R(%)
C (g kg^{-1})	16.5	6.12	10.38	63	7.38	1.26	12.1	7.50	1.38	13.3
N (mg kg^{-1})	1964	736	1228	63	821	85	6.9	939	203	16.5

In certain respects the conditions at the experimental site of Chan *et al.* (2001) were similar to those of the agro-ecosystems studied by Du Toit *et al.*(1994) and Lobe *et al.*(2001). Because of the lower rainfall and higher mean temperature at the Australian site, the aridity index would probably be even lower than that at Kroonstad. With regard to C degradation, however the Chan *et al.* (2001) site had the advantage of a far higher clay content, approximately double that of the Harrismith, Tweespruit, and Kroonstad agro-ecosystems. The overall comparability of the sites is however shown by the C_0 values, i.e. Chan *et al.* (2001) with 16.5 g kg^{-1} compared to Harrismith, Tweespruit, and Kroonstad with values of 19.5, 12.1, and 7.8 g kg^{-1} respectively. The higher C_0 value for Harrismith, in spite of a coarser textured soil, is probably due to the very much lower mean annual temperature of 13.8°C compared to 18.8°C for the agro-ecosystem studied by Chan *et al.* (2001).

Research results regarding C restoration by the establishment of perennial pastures already reviewed are presented in condensed form in Table 2.8, together with some additional results. The values for restoration percentage per year in the second last column are of particular importance since they make it possible to compare the results of the different research workers. If the C restoration rate was linear in relation to time, dividing these figures into

Table 2.8 Restoration of C in old cultivated lands placed under perennial pasture. Meaning of abbreviations as defined in the beginning of the dissertation.

Country	Region	Climate			Soil				Land history		C						Reference
		MAR (mm)	AI	Ta (^{0}C)	Type*	Texture	Clay (%)	SD (mm)	PCP (yrs)	RP (yrs)	C_0 (mg kg^{-1})	C_e (mg kg^{-1})	C_p (mg kg^{-1})	DL (%)	R (%)	R % yr^{-1}	
Australia	NSW	431	-	18.8	Re	ClLm	32	100	50	4	16.5	6.1	7.4	63	12	3.0	Chan *et al.* (2001)
USA	Texas	890	-	19.5	Ve	Cl	>45	50	100	6	59.5	18.0	22.2	70	10	1.7	Potter *et al.* (1999)
									100	26	44.4	15.3	24.5	66	32	1.2	Potter *et al.* (1999)
									100	60	54.9	18.8	38.6	66	55	0.9	Potter *et al.* (1999)
USA	Wyoming (Keeline)	403	2.8	7	AH	SaLm	$\pm$10	100	60	4	9.6	7.4	10.1	23	123	30.8	Reeder *et al.* (1998)
	Wyoming (Arvada)	304	2.1	7	UH	ClLm	$\pm$34	75	60	4	15.8	11.7	12.1	26	10	2.5	Reeder *et al.* (1998)
USA	Texas	430	-	-	AP	fiSaLm	-	50	30	5	4.7	0.8	1.1	83	8	1.6	Gebhart *et al.* (1994)
	Kansas	500	-	-	AH	fiSiLm	-	50	57	5	21.3	9.5	13.5	55	34	6.8	Gebhart *et al.* (1994)
	Nebraska	480	-	-	UP	fiSa	-	50	9	5	14.1	5.4	6.2	62	9	1.8	Gebhart *et al.* (1994)

*Re = Red earth, Ve = Vertisol, AH = Aridic Haplustoll, UH = Ustollic Haplargid, AP = Aridic Paleustalf and UP = Typic Ustipsamment

100 would give the estimated time required to restore the C content to what it was in the virgin soil, viz. C_0. The most favorable agro-ecosystem is shown to be the one of Keeline in Wyoming having an Aridic Haplustoll soil with 8-12% clay, mean annual rainfall of 403 mm, and a very low mean annual temperature of 7°C. This complete restoration of the 0-100 mm layer in less than 4 years, or 31% per annum, indicates very efficient C sequestration compared to the other agro-ecosystems recorded in Table 2.8, with comparable values ranging from 0.9 to 6.8% per annum, indicating minimum periods for complete restoration in the 0-50 mm layer of ranging from 15 to 100 years. As the restoration rate is however expected to decrease with time (Reeder *et al.*, 1998: Bruce *et al.*, 1999), and in fact is shown to do so by the data of Potter *et al.* (1999) in Table 2.8, the period for complete restoration can be expected to be considerably longer than these estimated values. There are also many factors, other than natural resource factors, such as fertility level, type of pasture planted, and management, which will influence the period for complete C restoration.

2.3.3 Red loam soils in Gauteng, South Africa

The value of having sufficient N in the soil to ensure effective C restoration under pastures was stressed by Theron & Haylett (1953). A pasture restoration experiment was established by them on the experimental farm of the University of Pretoria to test this hypothesis. The treatments with $(NH_4)_2SO_4$ on the red loam soil that had previously been under continuous cultivation for 17 years were as follows: 0(N0), 57(N1) and 114(N2) kg N ha^{-1} yr^{-1}. After 6 years the results for the 0-300 mm layer were N0 = 16.1, N2 = 16.6 and N3 = 17.5 g C kg^{-1} soil. The N1 treatment was not significantly different from N0 but N2 was significantly different from N0. There was no shortage of P in the soil. Although these results do not provide convincing support for the hypothesis of Theron & Haylett (1953), it needs to be said that the N content of the N0 treatment after 6 years of pasture was 1050 mg kg^{-1}. They unfortunately failed to determine the C and N contents at the start of the restoration period but made the reasonable assumption that these values would have been approximately the same as in the N0 treatment 6 years later. Judging by the N_0 (Equation 2.2) values for the 0-200 mm layers of the three agro-ecosystems Harrismith, Tweespruit, and Kroonstad presented in Table 2.3 (for example 1400, 1155 and 722 mg kg^{-1} respectively), 1050 mg kg^{-1} for the 0-300 mm layer is a relatively high value. If there is a threshold value of total soil N below which C sequestration under perennial pastures is impaired, then it seems probable that for an agro-ecosystem such as the Pretoria one studied by Theron & Haylett (1953), it will be below 1000 mg kg^{-1} for the 0-300 mm layer, and considerably lower for agro-ecosystems such as Tweespruit and Kroonstad.

2.4 CONCLUSION

This concise literature review reveals that a thorough knowledge of both the degradation and restoration process of SOM on cultivated lands from different agro-ecosystems is essential when aiming at sustainable crop production in future. It seems that currently the degradation process is far better understood than the restoration process with respect to SOM on cultivated lands. There is general consensus among researchers worldwide that the degradation pattern of SOM with time is exponential in nature, viz. an initial rapid rate of decline that slows down after some period to reach, eventually, a new equilibrium. At this new equilibrium the SOM content of cultivated lands is usually 40 to 70% lower than that of nearby native grasslands. The restoration of SOM is possible by the conversion of cultivated land to perennial pasture. In any agro-ecosystem it may take twice the length of the degradation period to restore SOM to what it was in native grassland.

When considering C restoration of degraded cultivated lands placed under perennial pastures, the generalized hypothetical shape of the restoration curve with time is important. Thompson & Troeh (1973) suggested that during pedogenesis, starting from raw parent material SOM accumulation with time follows a sigmoidal curve. They described the process as follows: "During the first few years there is little vegetative growth, primarily because of lack of N since rocks and minerals are generally very deficient in N. There is a gradual addition of N to soil by rainfall and through fixation of N by microorganisms. The growth of plants is accelerated by the increase in N and SOM. After a period of several decades, possibly several centuries, the accumulation of SOM begins to slow down and finally levels off to an approximately constant amount for the particular set of environmental conditions". It seems reasonable to propose that C restoration under perennial pastures will follow a similar sigmoidal pattern, something like a typical growth curve. The slow start is noted by Theron (1949), and a slowing down after about a decade is suggested by Bruce *et al.* (1999).

Additional information regarding C restoration in soils in the United States of America and Canada is presented by Bruce *et al.* (1999). They consider that a reasonable estimate of C gain in soils after the adoption of improved conservation tillage techniques, e.g. no-till is about 0.3 Mg ha^{-1} yr^{-1}, and after conversion of previously cultivated land to perennial pasture about 0.8 Mg ha^{-1} yr^{-1} in the first decade and ± 75% of that during the second decade.

CHAPTER 3

CHARACTERISTICS OF THE AGRO-ECOSYSTEMS AND THE STUDY SITES

3.1 INTRODUCTION

Decline in SOM is a major factor influencing the sustainability of dryland crop production in South Africa. This is particularly true of certain agro-ecosystems in the semi-arid to sub-humid summer rainfall regions of the Free State. As the literature review in Chapter 2 reveals, this decline in SOM is closely associated with natural resource and management factors and important ones among the former are rainfall, temperature and soil texture.

Detailed studies on SOM degradation of three agro-ecosystems in the Free State Province have been undertaken on fairly coarse textured soils with clay contents in the A horizon ranging from approximately 7 to 17%, with a soft plinthic B horizon at a depth of around 600 mm or shallower. Relevant results of these studies as presented by Du Toit *et al.* (1994) and Lobe *et al.* (2001) have been reviewed in detail in Chapter 2. It was decided therefore that it would be convenient and fruitful to study SOM restoration on the same three agro-ecosystems where cultivated land was coverted to perennial pasture.

3.2 MATERIALS AND METHODS

3.2.1 Selection of the agro-ecosystems and study sites

The emphasis of this research on the three agro-ecosystems studied by Du Toit *et al.* (1994) and Lobe *et al.* (2001), viz. Harrismith, Tweespruit and Kroonstad (Figure 2.1) was on SOM restoration from an area of land which had been under cultivation for more than 20 years, and which had then been under perennial pasture for at least five years. All the study sites selected within an agro-ecosystem were similar with regard to soil, climate and topography, and also similar to those studied by Du Toit *et al.* (1994) and Lobe *et al.* (2001). The soils were mainly of the Avalon and Westleigh forms (Soil Classification Working Group, 1991), which can be described also as Plinthosols (FAO, 1998) or Plinthustalfs (Soil Survey Staff, 1998).

Twenty eight suitable sites including eight from the Harrismith agro-ecosystem, eight from the Tweespruit agro-ecosystem, and twelve from the Kroonstad agro-ecosystem were selected in the field. To be included in the selection it was decided that a site had to meet the following criteria:

- The period of continuous cultivation preceding the establishment of perennial pasture must exceed 20 years.
- The period under subsequent perennial pasture must be five years or longer.
- With regard to location, topography and soil the site must be representative of a large area, i.e. the site must not be in an atypical small corner of a land.
- The clay content of the topsoil must be approximately between 10 and 16%.
- The colour of the AB or B horizon must be yellow as in typical Avalon and Westleigh soil forms
- The soft plinthic B horizon should be present within a depth of approximately 700 mm from the surface.

3.2.2 Sampling procedure and analytical methods

3.2.2.1 Site information

The following activities were carried out in the field:

1. Obtaining the history of a site from the farmer, especially the period of cultivation before perennial pasture establishment, and thereafter deciding whether or not a site fitted the stipulated criteria in this regard.
2. Estimating the clay content of the topsoil by the "feel" method to decide whether or not the soil fitted the pre-determined textural criteria.
3. Determination of the site location on a 1: 50 000 topocadastral map with 20 m contour lines.

4. Identification of the terrain morphological unit and aspect with the support of a 1:50 000 topocadastral map.
5. Classification of the soil at the form level, by augering to the soft plinthic B horizon.
6. Rating of the grass sward density on a scale of 1 to 5 with 1 = sparse, 2 = slightly sparse, 3 = moderately dense, 4 = dense and 5 = very dense or complete cover (Plates 3.1 to 3.4), and identification of grass species where possible since SOM restoration is closely correlated to biomass production, making the density of the vegetative cover and the type of vegetation important.

The following activities were carried out in the office:

1. Determination of coordinates, altitude and slope of the sites on 1:50 000 topocadastral maps with 20 m contour lines.
2. Transfer of site positions to 1:250 000 Land Type maps to identify the land type.
3. Employing the relevant Land Type Memoir to identify the climate zone, and extraction of the necessary data from the tables presented there.
4. Obtaining long-term rainfall data for each climate zone from the agro-meteorological data base at the ARC - Institute for Soil Climate and Water in Pretoria, to enable calculation of the mean annual rainfall during the period under pasture.

3.2.2.2 Sampling procedure

Sampling depths at each site were 0-50, 50-100, and 100-200 mm. Six replicate samples were taken at each site with each replicate sample consisting of a composite of six sub-samples taken from six points in a circle radius of 2 m. Augers were used to take the samples but care was taken to locate auger points alternatively on bare soil and on, or close to, a grass tuft. The soil samples were placed in labelled plastic bags and taken to the laboratory. After removing big stones, roots, leaves and stems of perennial pasture, the samples were dried by spreading out on labelled flat plastic sheets. Air dry samples were mixed thoroughly, transferred to labelled plastic bags and taken to the grinding room where they were ground with a pestle and mortar to pass through a 2 mm sieve. Finally the sieved samples were again mixed thoroughly

Plate 3.1 Fifteen year old pasture with a grass sward density of 2 at site 6 in the Harrismith agro-ecosystem.

Plate 3.2 Twenty five year old pasture with a grass sward density of 3 at site 7 in the Harrismith agro-ecosystem.

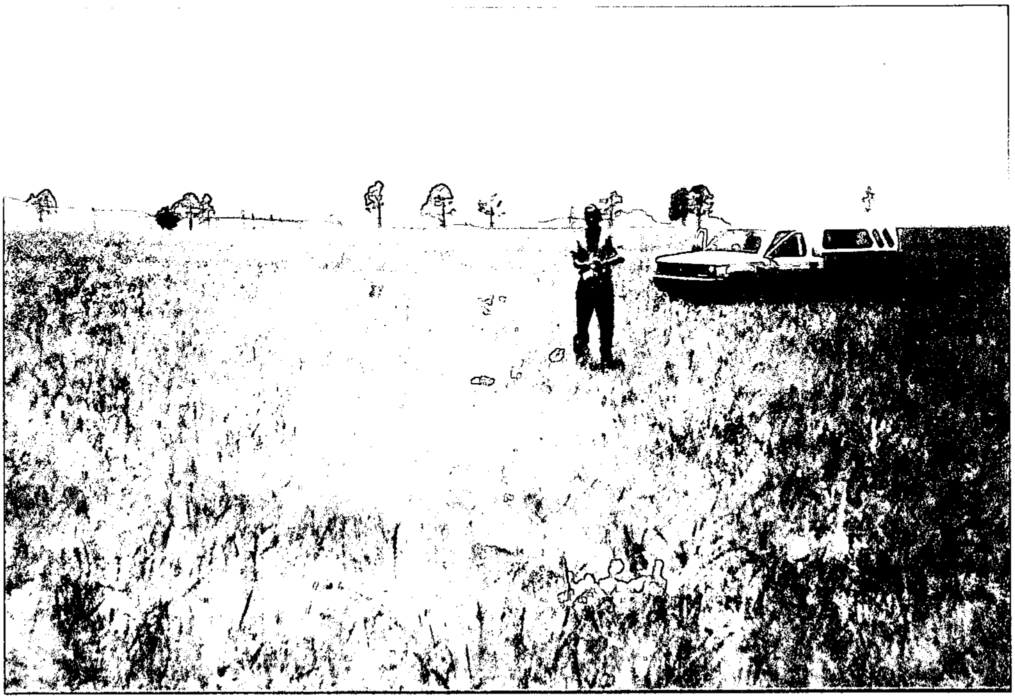


Plate 3.3 Fifteen year old pasture with a grass sward density of 3 at site 5 in the Harrismith agro-ecosystem. Three of the six sampling points are indicated by the sample bags.

Plate 3.4 Fourteen year old pasture with a grass sward density of 5 at site 2 in the Harrismith agro-ecosystem. The edge of the Drakensberg escarpment, just visible in left hand background, creates a micro-climate which promotes pasture growth and organic accumulation.

before they were transferred back to their plastic bags and stored until analyses were made. The final number of samples was 504.

3.2.2.3 Analytical methods

In conducting soil analyses for this study the procedures followed were those described in the "Handbook of Standard Soil Testing Methods for Advisory Purposes" (The Non-Affiliated Soil Analysis Work Committee, 1990). A concise description of each procedure used in this study follows.

Particle size distribution: Determined by a sieve and pipette method. A soil suspension containing 10% calgon solution as dispersing agent was stirred at high speed with a mechanical shaker for 10 minutes and after the appropriate settling time the supernatant containing the silt and clay fractions was decanted through a 0.05 mm sieve into a 1000 ml measuring cylinder. The sand which remained on the sieve was separated into coarse (2-0.5 mm), medium (0.5-0.25 mm) and fine (0.25-0.05 mm) sand fractions using appropriate sieve sizes. The pipette method was used to separate the coarse silt (0.05-0.02 mm), fine silt (0.02-0.002 mm) and clay (< 0.002 mm) fractions.

pH: A pH meter with combined glass electrodes was used to determine pH in 1: 2.5 soil to H_2O and in 1: 2.5 soil to 1N KCl suspensions.

Organic carbon: Determined by the Walkley-Black method in which 0.5N $K_2Cr_2O_7$ solution, followed by concentrated H_2SO_4, is added to soil for oxidizing the organic C therein to CO_2. The excess dichromate was back titrated with 0.2N Fe $(NH_4)_2(SO_4)_2.6H_2O$ solution.

Total nitrogen: Determined by the regular Kjeldahl method in which the organic N is converted to NH_4^+-N by the reaction of concentrated H_2SO_4 in the presence of a catalyst , viz. a mixture of $CuSO_4.5H_2O$, K_2SO_4 and $Na_2Se_2O_4$. The mixture was then steam distilled with 8.0N NaOH to convert the NH_4^+-N to NH_3-N. The NH_3 released was absorbed in boric acid and titrated against 0.005N H_2SO_4.

Extractable phosphorus: Determined by two methods, viz. the Olsen method using 0.5N $NaHCO_3$ at pH 8.5 as the extracting solution and shaking the suspension for 30 minutes, and the Bray method using 0.03N NH_4F mixed with 0.1N HCl as extracting solution, and shaking the suspension for 1 minute. The P concentration in the extraction was then determined by means of spectrophotometry.

Exchangeable cations and CEC: A soil sample was leached with 1N NH_4OAc adjusted to pH 7. The filtrate was used for the determination of the exchangeable cations Ca^+, Mg^{++}, K^+, and Na^+ using an atomic absorption spectrophotometer. The NH_4^+ saturated soil sample was leached with 1N NaOAc adjusted to pH 8.2 followed by a series of washings with alcohol. The sample was then leached with 1N NH_4OAc adjusted to pH 7 and the filtrate used to determine the CEC via Na^+ by an atomic absorption spectrophotometer.

The determinations for pH, organic C and total N were made on all the samples. Particle size distribution was determined only on the samples from the 50-100 mm layer. For the determination of P, exchangeable cations and CEC, a single representative composite sample was prepared for analysis by mixing subsamples from the three layers, viz. 0-50, 50-100, and 100-200 mm in a ratio of 1:1:2. The C:N ratio, percent base saturation, percent acid saturation and CEC of the clay were calculated from the analytical data. All these data are presented in Appendices 1 to 3.

3.2.3 Statistical analysis

One way analysis of variance was used to test the significant difference between the averages of the parameters under consideration in the three agro-ecosystems. The averages may be compared with the Du Toit *et al.* (1994) and Lobe *et al.* (2001) reference values. Least significance differences or any other appropriate comparison method was used to compare averages of soil properties.

3.3 CHARACTERISTICS OF THE STUDY SITES WITHIN EACH AGRO-ECOSYSTEM

3.3.1 Harrismith agro-ecosystem

3.3.1.1 Climate

Two climate zones, viz. 77S and 82S characterize the sites in the Harrismith agro-ecosystem. Details of these two climate zones are presented in Table 3.1. The two climates are very similar with dry cold winters and a frost period of about six months from April to September. Most of the rain falls from October to March and mean temperatures during these months are moderate, ranging from 16 to 19°C. Climate zone 82S is slightly warmer and drier in summer than climate zone 77S, which produces the considerable difference in the aridity indices, i.e. 0.39 and 0.46 respectively. The climate difference may be associated with the altitude. Site 3 in climate zone 82S has a lower altitude of 1712 m than most of the sites in climate zone 77S with a mean of 1770 m.

3.3.1.2 Sites

Details of the eight sites in the Harrismith agro-ecosystem are presented in Table 3.2. The similarity of the different sites is confirmed by the following facts: they all belong to the same broad Land Type group Bb; all the sites except one occur in climate zone 77S; all the soils belong to the Avalon form with the soft plinthic B horizon generally at a depth of $\pm$600 mm; the terrain morphological unit is generally 3; except for one site the slopes are all 4% or less. The period under perennial pasture ranges from 5 to 25 years, the main grass varieties being *Eragrostis curvula*, Smuts finger, Tall fescue (only sites 3 and 4) and other mixed grasses. With respect to management, most sites were fertilized with limestone ammonium nitrate at rates varying from 28 to 84 kg N ha^{-1} yr^{-1}. Only two sites, viz. 3 and 4 received applications of P. Examples of unusual management practices were site 3 which was irrigated, and site 5 which received no fertilizer during the last five years and was burnt each spring. The perennial pastures were used mainly for grazing at sites 1 and 6, whereas at sites 2, 3, 4, 5, 7 and 8 the grass was sometimes cut for hay and sometimes grazed. The grass sward density at sites 2, 3

Table 3.1 Climate data for the Harrismith agro-ecosystem (Land Type Survey Personnel, 1984-2001). Meaning of abbreviations as defined in the beginning of the dissertation

Climate zone 77S: Sites 1, 2, 4, 5, 6, 7 and 8													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
MAR (mm)	116	101.3	76.2	39.3	21.7	9.4	11.9	17.3	35.7	72.1	100	105	706.1
E_0 class-A pan (mm)	195	156.8	146	114	86.8	57	62	93	120	158	171	195	1550
AI	0.59	0.65	0.52	0.34	0.25	0.16	0.19	0.19	0.30	0.46	0.59	0.54	0.46
Tmax (°C)	29.9	28.4	26.3	24.2	21.4	19.4	19.8	23.4	26.7	28.8	29	29.3	25.6
Tmin (°C)	6.6	7.1	4.6	0.9	-2.8	-4.8	-4.6	-3.8	-2.1	1.6	3.2	0	0.5
Tm (°C)	18.3	17.8	15.45	12.6	9.3	7.3	7.6	9.8	12.3	15.2	16.1	14.7	13.0
Climate zone 82S: Site 3													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
MAR (mm)	109.7	84.4	75.6	42.2	23.8	9.0	10.8	15.0	30.9	69.8	89.8	95.4	656
E_0 class-A pan (mm)	177	157	127	102	105	87.0	102	133	165	177	177	174	1683
AI	0.62	0.54	0.59	0.41	0.23	0.10	0.11	0.11	0.19	0.40	0.51	0.55	0.39
Tmax (°C)	31.4	30.5	29.1	26.5	24.0	20.4	20.5	24.4	28.3	30.1	30.3	31.2	27.2
Tmin (°C)	8.0	7.3	5.6	-0.1	-4.0	-7.4	-7.5	-5.9	-1.9	1.7	4.0	6.8	0.6
Tm (°C)	19.7	18.9	17.4	13.2	10.0	6.5	6.5	9.3	13.2	15.9	17.2	19.0	13.9

Table 3.2 Detailed description of the sampling sites in the Harrismith agro-ecosystem. Meaning of abbreviations as defined in the beginning of the dissertation

Site	Coordinates		Land type	Altitude (m)	Climate zone	Soil form	TMU	Aspect	Slope (%)	Depth to soft plinthic (mm)	Years under pasture	Management		GSD	MARP (mm)
	South	East										Fertilization	Utilization		
1	28°27'15"	29°08'45"	Bb121	1687	77S	Av	3	NE	10	600	12	Not fertilized	Grazing	2	637
2	28°26'39"	29°12'42"	Bb121	1760	77S	Av	1	E	0.5	600	14	First 11 yrs 28 kg N ha^{-1} yr^{-1}; not fertilized last 3 yrs	Grazing and hay	5	652
3	28°11'39"	29°09'35"	Bb25	1712	82S	Av	3	NE	4	600	5	First 4 yrs 70 kg N $ha^{-1}yr^{-1}$; last year 200 kg N ha^{-1} and 65 kg P ha^{-1}; supplemental irrigation	Seed and hay	5	1020
4	28°10'00"	29°18'49"	Bb28	1823	77S	Av	3	N-NW	2	600	7	At planting 26 kg N ha^{-1} and 13 kg P ha^{-1}; first 5 yrs 84 kg N $ha^{-1}yr^{-1}$; not fertilized last 2 yrs	Grazing and hay	5	676
5	28°10'08"	29°16'02"	Bb28	1834	77S	Av	3	N	4	600	±15	First 10 yrs 40 kg N ha^{-1} yr^{-1}; not fertilized last 5 yrs; burnt each spring for last 5 yrs	First 10 yrs hay; last 5 yrs sheep grazing	3	652
6	28°09'28"	29°15'36"	Bb28	1820	77S	Av	3	NE	1	400	±15	First 5 yrs 60 kg N $ha^{-1}yr^{-1}$; not fertilized last 10 yrs	Grazing	2	652
7	28°26'32"	29°06'20"	Bb121	1714	77S	Av	1/3	W	3.5	600	25	Since planting 84 kg N ha^{-1} yr^{-1}	Hay; residue grazed or burnt	3	642
8	28°24'24"	29°08'49"	Bb121	1750	77S	Av	3	SW	3.5	600	6	Since planting 55 kg N $ha^{-1}yr^{-1}$ and 10 kg P $ha^{-1}yr^{-1}$	Hay	4	707

Table 3.3 Some physical and chemical soil properties in the 0-200 mm soil layer of sampling sites in the Harrismith agro-ecosystem. Meaning of abbreviations as defined in the beginning of the dissertation.

Site	coSa (%)	meSa (%)	fiSa (%)	coSi (%)	fiSi (%)	Cl (%)	Texture class	pH (1:2.5)		P (mg kg^{-1})		Exchangeable cations (mg kg^{-1})				CEC (cmol$_c$ kg^{-1})		BS (%)	AS (%)
								H_2O	KCl	Olsen	Bray	Ca	Mg	K	Na	Soil	Clay		
1	0.1	10.6	60.1	6.1	7.6	13.2	fiSaLm	5.2	4.1	1.3	2.5	314	85	129	10	4.8	36.4	56	44
2	1.1	13.2	51.9	7.2	8.9	16.6	fiSaLm	4.6	3.9	6.0	15.1	232	51	37	12	6.3	38.3	28	72
3	0.4	3.8	68.7	5.4	7.8	13.5	fiSaLm	5.5	4.4	4.2	10.4	670	120	159	25	5.0	38.7	98	2
4	1.7	10.6	67.7	5.0	4.2	12.4	fiSaLm	5.1	4.0	36.1	165.0	288	74	221	19	4.4	35.6	63	37
5	2.4	22.9	52.3	6.9	4.7	11.3	fiSaLm	4.6	4.0	3.8	15.3	338	49	66	13	4.1	35.9	57	43
6	2.1	10.8	62.1	7.5	5.1	12.8	fiSaLm	5.7	4.8	8.4	32.1	482	76	140	13	4.6	36.0	75	25
7	0.4	27.6	44.7	6.8	6.7	13.5	fiSaLm	5.2	4.0	4.2	19.2	335	55	36	18	4.4	32.7	53	47
8	0.5	22.3	49.4	6.7	8.2	11.5	fiSaLm	5.3	4.4	9.3	42.2	525	100	136	23	6.7	58.7	59	41
Mean	1.1	15.2	57.2	6.3	6.6	13.1	fiSaLm	5.2	4.2	9.2	37.7	398	76	115	17	5.0	39.0	61	39
LSD (0.05)	0.5	6.2	5.9	1.7	1.5	1.6	-	0.2	0.1	2.3	10.2	118	15	37	4	0.7	7.3	18	18

and 5 was high, and therefore the complete cover index of 5 was allotted, whereas at sites 1 and 6 the density was very poor. The rate of SOM restoration gain at the latter two sites can therefore be expected to be very low. The mean annual rainfall during the period under pasture ranges between 642 to 707 mm over the different sites indicating relatively uniform rainfall conditions during the restoration periods.

3.3.1.3 Soils

Selected physical and chemical properties of the soils from the different sites in the Harrismith agro-ecosystem are presented in Table 3.3. The clay content variation between sites is small, with only site 2 (16.6%) falling out of the range 11.5 to 13.5%. The texture at all the sites was fine sandy loam. The data in Table 3.4 will be used as a reference for the discussion of the fertility status of the different sampling sites. In general the pH(H_2O) is slightly low with a mean at 5.2 but sites 2 and 5 have low values of 4.6. Excepting for site 4, and possibly 6 and 8, P is shown to be medium to low at the other sites, and extremely low at site 1. Both Ca and Mg are medium to low at all the sites excepting sites 3 and 8 where the values are medium to high. The K is medium to low at sites 2, 5 and 7, and high at all the other sites. There is little variation between sites in the generally low CEC values for soil with a mean of 5 $cmol_c\ kg^{-1}$. At site 3 the exchange complex is close to being saturated with bases, but the base saturation at all the other sites is relatively low, with a mean value of 55%.

3.3.2 Tweespruit agro-ecosystem

3.3.2.1 Climate

In the Tweespruit agro-ecosystem all the sites occur in climate zone 105S. Details of this climate zone are presented in Table 3.5. The data shows that 89% of the rain falls from October to March, which is therefore the growing season, with mean temperatures ranging from 16 to 21°C, and a mean aridity index of 0.37 for these months.

Table 3.4 Threshold values for some parameters indicating the fertility status of soils in the Free State, South Africa (Adapted from FSSA, 1994).

Parameters	Threshold value (mg kg^{-1})		
	Low	Medium	High
pH (H_2O)	< 5.5	5.5 - 6.5	> 6.5
pH (KCl)	< 4.5	4.5 - 5.5	> 5.5
N (KCl)	< 5	5 - 15	> 15
P (Olsen)	< 6	6 - 12	> 12
P (Bray)	< 15	15 - 25	> 25
K (NH_4OAc)	< 40	40 - 80	> 80
Ca (NH_4OAc)	< 400	400 - 600	> 600
Mg (NH_4OAc)	< 50	50 -100	> 100

3.3.2.2 Sites

Details of the eight sites in the Tweespruit agro-ecosystem are presented in Table 3.6. Evidence for the similarity of the eight sites is provided by the following facts: they all occur in Land Type Ca33 and climate zone 105S, and are close together (within a circle of radius of $\pm$ 2 km); they occur on adjacent farms belonging to one farmer and therefore the management of the pasture is expected to be reasonably uniform; their altitude is very similar with a range of 1601 to 1628 m and mean of 1606 m; the aspect is generally north with gentle slopes between 0.5 and 3%; all soils are of the Westleigh form with the depth to the soft plinthic B horizon between 250 and 300 mm. This homogeneity is advantageous for the purpose of assessing SOM restoration gains with different periods under perennial pasture. Fertilization was unfortunately not homogeneous.

3.3.2.3 Soils

Relevant physical and chemical properties of the soils from the different sites in the Tweespruit agro-ecosystem are presented in Table 3.7. The textures of the topsoils sampled

Table 3.5 Climate data for the Tweespruit agro-ecosystem (Land Type Survey Personnel, 1984-2001). Meaning of abbreviations as defined in the beginning of the dissertation.

Climate zone 105S: All the sites													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
MAR (mm)	94.8	83.2	93.7	54.2	24.3	10.0	11.2	15.6	23.3	57.2	79.6	75.8	544.4
E_0 class-A pan (mm)	279	202	180	132	102	75.0	86.8	133	165	208	228	245	2035
AI	0.34	0.41	0.52	0.41	0.24	0.13	0.13	0.12	0.14	0.28	0.35	0.31	0.27
Tmax (°C)	33.5	29.7	29.7	25.7	23.5	20.2	22.3	25.6	28.5	30.8	31.8	32.4	27.8
Tmin (°C)	9.4	9.0	6.7	1.7	-2.1	-5.7	-5.4	-5.0	-1.7	0.8	5.7	8.1	1.8
Tm (°C)	21.5	19.4	18.2	13.7	10.7	7.3	8.5	10.3	13.4	15.8	18.8	20.3	14.8

Table 3.6 Detailed description of the sampling sites in the Tweespruit agro-ecosystem. Meaning of abbreviations as defined in the beginning of the dissertation

Site	Coordinates		Land type	Altitude (m)	Climate zone	Soil form	TMU	Aspect	Slope (%)	Depth to soft plinthic (mm)	Years under pasture	Management		GSD	MARP
	South	East										Fertilization	Utilization		
1	29°15'50"	27°01'17"	Ca33	1601	105S	We	Lower 3	N	2	250	11	limed	Grazing	2	616
2	29°15'35"	27°01'42"	Ca33	1596	105S	We	3	N	2.5	250	10	limed	Grazing	4	623
3	29°15'45"	27°01'45"	Ca33	1602	105S	We	1/3	NE	0.5	250	7	limed	Grazing	3	686
4	29°18'13"	27°02'00"	Ca33	1602	105S	We	Upper 3	N	3	250	9	limed	Grazing	4	642
5	29°17'26"	27°01'35"	Ca33	1621	105S	We	3	N	1.5	250	14	46 kg N ha^{-1}yr^{-1} plus lime	Grazing	3	693
6	29°16'53"	27°02'07"	Ca33	1595	105S	We	Lower 3	N	3	300	25	46 kg N ha^{-1}yr^{-1} plus lime	Grazing	5	688
7	29°17'00"	27° 02'10"	Ca33	1603	105S	We	Middle 3	N	1	300	8	46 kg N ha^{-1}yr^{-1} plus lime	Grazing	5	663
8	29°17'25"	27° 00'33"	Ca33	1628	105S	We	Lower 3	SE	1.6	250	5	46 kg N ha^{-1}yr^{-1} plus lime	Grazing	3	741

Table 3.7 Some physical and chemical soil properties in the 0-200 mm layer of the sampling sites in the Tweespruit agro-ecosystem. Meaning of abbreviations as defined in the beginning of the dissertation

Site	coSa (%)	meSa (%)	fiSa (%)	coSi (%)	fiSi (%)	Cl (%)	Texture class	pH (1:2.5)		P (mg kg^{-1})		Exchangeable cations (mg kg^{-1})				CEC ($cmol_c$ kg^{-1})		BS (%)	AS (%)
								H_2O	KCl	Olsen	Bray	Ca	Mg	K	Na	Soil	Clay		
1	0.5	9.2	63.9	8.1	6.6	12.9	fiSaLm	5.7	4.7	10.5	43.8	532	82	300	23	5.1	39.7	83	17
2	0.8	12.3	61.2	7.5	6.6	12.3	fiSaLm	6.1	5.1	11.0	33.2	900	104	170	23	5.0	39.5	100	0
3	1.1	5.1	75.4	5.2	4.5	10.4	LmfiSa	6.1	5.2	14.3	48.8	629	64	165	22	4.4	43.8	99	1
4	1.4	7.5	70.1	5.9	4.2	11.6	fiSaLm	5.8	5.0	17.8	71.4	717	60	203	19	4.3	36.6	100	0
5	1.7	10.4	64.6	10.3	4.9	8.6	LmfiSa	5.9	5.1	10.1	37.2	796	67	190	22	4.1	45.5	100	0
6	0.7	6.7	63.0	9.7	7.6	12.6	fiSaLm	5.4	4.5	14.8	50.2	589	74	205	28	4.7	37.9	92	9
7	0.5	12.0	64.1	6.9	6.1	9.5	fiSaLm	5.7	4.7	20.3	71.3	584	54	172	27	3.4	38.9	100	0
8	1.0	4.6	56.2	13.4	8.2	15.5	LmfiSa	5.4	4.5	18.3	58.6	753	102	126	28	5.7	36.9	90	10
Mean	1.0	8.5	64.8	8.4	6.1	11.7	fiSaLm	5.8	4.8	14.6	51.8	688	76	191	24	4.6	39.8	100	0
LSD (0.05)	0.3	3.0	3.5	2.2	1.2	2.0	-	0.1	0.1	13.5	4.2	88	18	23	5	1.0	11.3	27	27

are reasonably similar, with the clay content ranging from 8.6 to 15.5% and an average of 11.7%. Fine sand dominates the sand fraction with a range of 56 to 75% and an average of 65% of the total soil. Textures are either fine sandy loam or loamy fine sand. Using the fertility criteria specified in Table 3.4, the results show that the pH(H_2O) is medium with a mean of 5.8. At all sites the P content is medium to high. The Ca levels are mainly high while the Mg levels are mainly medium. Therefore the use of dolomitic lime instead of calcitic lime on the sites would be beneficial. At all eight sites the K content is very high. The CEC values of the soil range from 3.4 to 5.7 $cmol_c\ kg^{-1}$ with a mean of 4.6 $cmol_c\ kg^{-1}$. The base saturation at all sites is high with the mean value of 95%.

3.3.3 Kroonstad agro-ecosystem

3.3.3.1 Climate

The sampling sites of the Kroonstad agro-ecosystem occur in two climate zones, viz. 31S and 35S. Details of these two climate zones are presented in Table 3.8. The climate in the two zones is very similar with 31S having a slightly lower annual rainfall, higher annual evaporative demand, and therefore lower annual aridity index. Climate zone 31S is also slightly warmer in winter and summer than climate zone 35S. Assuming the growing season to be October to March the rainfall and the aridity index values for this period are 468 mm and 0.37 respectively for climate zone 31S, and 460 mm and 0.36 respectively for climate zone 35S. The period with frost in both climate zones is May to September, with mean temperatures and aridity indices for these months of 11.4°C and 0.15 for 31S, and 9.9°C and 0.12 for 35S, respectively.

3.3.3.2 Sites

Details of the twelve sites in the Kroonstad agro-ecosystem are presented in Table 3.9. The sites are spread out over an area contained approximately in a rectangle, elongated in a north to south direction, about 70 km long and 36 km wide. Two Land Types are represented, i.e. Bd16 with sites 7, 8, and 9, and Bd21 with the remaining sites spread over a relatively wide

Table 3.8 Climate data for the Kroonstad agro-ecosystem (Land Type Survey Personnel, 1984-2001). Meaning of abbreviations as defined in the beginning of the dissertation

Climate zone 31S: Sites 7, 8 and 9													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
MAR (mm)	96.4	82.8	83.2	39.6	17.8	6.5	6.9	7.0	15.4	45.7	76.7	82.6	560.6
E_0 class-A pan (mm)	232.5	187.6	173.6	129.0	108.5	90.0	105.4	148.8	198.0	235.6	228.0	248.0	2085.0
AI	0.41	0.44	0.48	0.31	0.16	0.07	0.07	0.05	0.08	0.19	0.34	0.33	0.27
Tmax (°C)	34.8	33.6	32.0	29.7	26.0	23.4	24.2	27.8	31.7	34.1	34.1	34.8	30.5
Tmin (°C)	10.8	11.0	7.8	2.4	-2.1	-5.2	-5.3	-3.8	-2.7	3.6	6.8	9.7	2.8
Tm (°C)	22.8	22.3	19.9	16.1	12.0	9.1	9.5	12.0	14.5	18.9	20.5	22.3	16.6
Climate zone 35S: Sites 1, 2, 3, 4, 5, 6, 10, 11 and 12													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
MAR (mm)	94.3	76.1	75.9	44.2	22.6	7.8	9.2	8.6	21.2	55.2	76.1	83.3	574.5
E_0 class-A pan (mm)	244.9	182	170.5	123.0	96.1	78.0	96.1	136.4	189.0	232.5	237.0	254.2	2039.7
AI	0.39	0.42	0.45	0.36	0.24	0.10	0.10	0.06	0.11	0.24	0.32	0.33	0.28
Tmax (°C)	33.4	32.3	30.6	27.8	25.0	21.5	21.8	25.7	30.1	32.1	32.7	32.7	28.8
Tmin (°C)	9.4	9.1	5.7	0.3	-3.9	-6.6	-7.5	-5.6	-2.4	2.7	4.6	7.8	1.1
Tm (°C)	21.4	20.7	18.2	14.1	10.6	7.5	7.2	10.1	13.9	17.4	18.7	20.3	15.0

Table 3.9 Detailed description of the sampling sites in the Kroonstad agro-ecosystem. Meaning of abbreviations as defined in the beginning of the dissertation

Site	Coordinates		Land type	Altitude (m)	Climate zone	Soil form	TMU	Aspect	Slope (%)	Depth to soft plinthic (mm)	Years under pasture	Management		GSD	MARP (mm)
	South	East										Fertilization	Utilization		
1	27°52'53"	26°58'30"	Bd21	1451	35S	Av	3	NE	1	500	20	Not fertilized	Cattle grazing	5	557
2	27°51'34"	26°56'33"	Bd21	1453	35S	Av	3	SE	1.5	550	17	Every 4^{th} yr 28 kg N ha^{-1}	Grazing	2	565
3	27°49'11"	26°59'13"	Bd21	1393	35S	Av	4	NE	< 0.5	700	8	50 kg P ha^{-1} yr^{-1}	Grazing	3	589
4	27°43'41"	27°01'17"	Bd21	1360	35S	Av	1	N	0.7	900	4	37 kg N $ha^{-1}yr^{-1}$	Grazing	3	576
5	27°40'28"	26°59'24"	Bd21	1342	34S	Av	3	SW	2		10	37 kg N $ha^{-1}yr^{-1}$	Grazing	3	564
6	27°41'41"	26°58'24"	Bd21	1326	35S	Av	Lower 3	W	3	450	5	37 kg N $ha^{-1}yr^{-1}$	Grazing and hay	3	625
7	27°24'09"	27°11'19"	Bd16	1412	31S	Av	3	N	1	400	9	Every 2^{nd} yr 60 kg N ha^{-1}	Grazing	3	573
8	27°23'03"	27°10'18"	Bd16	1417	31S	Av	Lower 3	N	0.7	500	10	Every 2^{nd} yr 60 kg N ha^{-1}	Grazing	3.5	564
9	27°22'34"	27°10'18"	Bd16	1396	31S	Av	Lower 3	W	0.7	400	8	Every 2^{nd} yr 60 kg N ha^{-1}	Grazing	2.5	589
10	27°15'24"	27°22'24"	Bd21	1367	35S	Av	Lower 3	N	0.7	500	18	Not fertilized	Grazing	2	562
11	27°15'26"	27°22'36"	Bd21	1386	35S	Av	Upper 3	W	1	500	18	Not fertilized	Grazing	3	562
12	27°48'49"	27°15'07"	Bd21		35S	We	1/3	SE	<1	350	5	Two yrs after planting 150 kg N ha^{-1}	Grazing	2	625

Table 3.10 Some physical and chemical soil properties in the 0-200 mm layer of the sampling sites in the Kroonstad agro-ecosystem. Meaning of abbreviations as defined in the beginning of the dissertation.

Site	coSa (%)	meSa (%)	fiSa (%)	coSi (%)	fiSi (%)	Cl (%)	Texture class	pH (1:2.5)		P (mg kg^{-1})		Exchangeable cations (mg kg^{-1})				CEC (cmol$_c$ kg^{-1})		BS (%)	AS (%)
								H_2O	KCl	Olsen	Bray	Ca	Mg	K	Na	Soil	Clay		
1	1.2	3.4	76.5	6.4	2.6	8.8	fiLmSa	5.8	4.7	19.5	123.0	497	89	326	25	4.7	53.3	89	11
2	3.0	8.9	68.4	4.5	3.3	10.7	fiSaLm	5.5	4.2	26.9	146.7	373	60	163	23	4.5	42.0	64	36
3	1.2	11.8	64.3	4.1	4.1	14.3	fiSaLm	5.9	4.8	13.9	58.2	840	100	374	23	5.7	40.9	100	0
4	2.0	13.7	72.7	2.6	1.2	7.3	fiLmSa	6.2	4.7	13.2	69.2	442	89	126	22	3.5	49.4	96	4
5	3.8	17.5	59.8	3.4	3.0	11.7	fiSaLm	5.3	4.2	7.4	36.4	647	142	154	24	5.5	44.8	89	11
6	4.4	20.9	60.8	2.6	1.8	10.0	fiLmSa	5.4	4.4	12.7	66.3	560	128	199	21	4.3	43.2	100	0
7	2.8	10.4	68.4	4.5	3.1	10.5	fiLmSa	5.7	4.6	13.8	47.1	554	122	300	21	3.7	36.5	100	0
8	2.7	13.6	61.5	3.4	4.0	14.2	fiSaLm	6.5	5.5	26.0	118.4	703	109	237	22	7.1	49.9	80	21
9	1.5	11.4	70.3	5.5	3.4	7.7	fiLmSa	5.7	4.6	21.1	80.9	257	64	207	19	4.7	66.8	49	51
10	4.4	17.1	55.2	6.7	4.8	11.5	fiSaLm	5.7	4.8	17.4	65.4	534	151	277	20	6.3	56.2	65	35
11	3.2	20.3	54.8	3.9	5.5	11.5	fiSaLm	5.5	4.5	11.5	45.7	436	91	286	23	6.8	59.3	56	44
12	6.2	9.4	61.1	8.3	4.9	8.8	fiSaLm	5.7	4.6	12.0	54.1	212	72	236	24	10.4	114.9	42	58
Mean	3.0	13.2	64.5	4.7	3.5	10.6	fiSaLm	5.7	4.6	16.3	75.9	505	102	240	22	5.6	54.8	82	18
LSD (0.05)	0.8	3.4	3.3	1.5	0.8	1.7	-	0.1	0.2	4.3	27.9	103	55	85	5	1.0	11.2	30	30

area. The altitude of the sites is similar varying from 1326 to 1453 m with a mean of 1389 m. The terrain morphological unit is commonly 3 with a gentle slope varying from 0.5 to 3% with various aspects. Excepting for site 12 with a Westleigh form soil, all the soils belong to the Avalon form with the depth to the soft plinthic B horizon varying from 400-900 mm. Relevant management practices were relatively low fertilizer applications of N only, and pastures used mainly for grazing. The grass sward density was generally rather low, with only site 1 being considered as having a complete cover. The mean annual rainfall for the period under pasture were reasonably similar with a mean value of 579 mm.

3.3.3.3 Soils

Some physical and chemical properties of the soils from the different sites in the Kroonstad agro-ecosystem are presented in Table 3.10. The variation in clay content is quite wide, i.e. from 7.3 to 14.3% with a mean of 10.6% and with the majority of sites having values below 12.5%. The sand fraction is dominated by fine sand and the texture class is loamy fine sand or fine sandy loam. According to the threshold values in Table 3.4 the pH(H_2O) of most sites is medium to high. All the sites have a P status of medium to high. The very high P concentrations at sites 1, 2 and 8 according to the Bray extraction are surprising. In general the Ca levels are medium to high with only sites 2 and 9 having low levels Also the Mg levels are generally medium to high at all 12 sites. The K levels are very high at all sites. At site 12 the soil's CEC of 10.4 $cmol_c\ kg^{-1}$ is considerably more than that at the other sites which average 5.2 $cmol_c\ kg^{-1}$. Base saturation varies widely between sites, viz. from 42 to 100%.

3.4 CONCLUSION

The foregoing information indicates that in each of the three agro-ecosystems studied by Du Toit *et al.* (1994) and Lobe *et al.* (2001) study sites were found which met the criteria set out initially. In each agro-ecosystem the study sites were to a large extent similar with regard to soil, climate and topography. Unfortunately, the management practices applied by the farmers on the perennial grass pastures varied between sites within an agro-ecosystem, especially the fertilization and utilization. These practices may have a marked influence on the restoration of SOM in perennial pastures. However, this selection of agro-ecosystems and the sites within each are of such a nature that it can contribute to our knowledge about SOM restoration in the semi-arid to sub-humid regions.

CHAPTER 4

ORGANIC MATTER RESTORATION BY CONVERSION OF CULTIVATED LAND TO PERENNIAL PASTURE

4.1 INTRODUCTION

It was explained in Chapter 3 that this study was conducted on the same agro-ecosystems as those on which C and N degradation curves were obtained by Du Toit *et al.* (1994) and Lobe *et al.* (2001). Their results are reviewed in Chapter 2 . It is necessary to keep in mind that in the former study the sampling depth was 0-200 mm, and that in the latter it was 0-100 and 100-200 mm. Raw data from their studies were combined to calculate what were considered to be representative values of C_0 and C_e (Equation 2.1), and of N_0 and N_e (Equation 2.2) for the 0-200 mm layer for each agro-ecosystem. Because the depth of cultivation is generally approximately 0-200 mm, it has been assumed that after a long period of cultivation the C and N contents (C_e and N_e) in this layer will be reasonably homogeneous, i.e. C_e (0-50 mm) = C_e (50-100 mm) = C_e (100-200 mm), and similarly for N_e.

In virgin soils, however, as is clearly shown in the literature review, there is a sharp decrease in C and N content with depth. A similar trend can therefore be expected in soils in which organic matter restoration under perennial pastures is occurring. That was the reason for the choice of the sampling depths in this study being 0-50, 50-100 and 100-200 mm. For the comparison of the C and N contents of soils undergoing restoration under perennial pastures, viz. C_p and N_p with C_e and N_e, because of the assumption already explained, the comparisons of C_p (0-50 mm), C_p (50-100 mm) and C_p (100-200 mm) with C_e (0-200 mm) are valid, and similarly for comparisons of N_p (0-50 mm), N_p (50-100 mm) and N_p (100-200 mm) with N_e (0-200 mm). However, for the comparison of C_p with C_0, or N_p with N_0, this validity does not hold. Under the prevailing circumstances the best that could be done was to consider that C_0 (0-100 mm) is approximately equal to either C_0 (0-50 mm) and C_0 (50-100 mm), and similarly for N_0. This was useful since in the raw data of Lobe *et al.* (2001) there are values for C_0 (0-100 mm) and N_0 (0-100 mm).

Because of the importance of C sequestration in relation to global warming, in a number of recent research reports (Bruce *et al.*, 1999; Lal, 2001) C gains are expressed in terms of Mg ha^{-1}. As Lobe *et al.* (2001) determined soil bulk density on the three agro-ecosystems, it is possible to express the results of this study in these units. Based on the bulk density results of Lobe *et al.* (2001) a mean value of 1.4 Mg m^{-3} is considered to be reasonable for the 0-200 mm layer of the three agro-ecosystems. Gains of C in terms of concentration (C_p - C_e) were determined for each of the 0-50, 50-100 and 100-200 mm layers separately, converted to quantities per hectare using a bulk density value of 1.4 Mg m^{-3} and then added together to get an overall value for the 0-200 mm layer. This value was then divided by the duration of the restoration period to give the final result in terms of Mg ha^{-1} yr^{-1}.

In order to try to understand the C gain under perennial pasture in the different agro-ecosystems, and at the different sites, it was considered useful to make an estimate of the mean amount of N available to the pasture during the restoration period. This was done by assuming a mineralization rate of 3%. For estimating the amount of N mineralized the N content was taken as $(N_e + N_p)/2$, i.e. the approximate N content at the middle of the restoration period. With regard to N added as fertilizer during the restoration period, it was assumed that because of the relatively long periods involved, its benefit would be expressed in the total N analytical result.

4.2 ORGANIC MATTER IN PERENNIAL PASTURE SOILS COMPARED TO CULTIVATED AND VIRGIN SOILS

4.2.1 Harrismith agro-ecosystem

4.2.1.1 Organic carbon

4.2.1.1.1 Comparing C_p with C_e

The main characteristics of each site considered important with regard to C sequestration are summarized in Table 4.1, together with the total C gains during the restoration period expressed as Mg $ha^{-1}yr^{-1}$. For the qualitative nutrient level assessment threshold values were taken from Table 3.4. The C contents at the different sites and for the different layers are presented in Figure 4.1.

Restoration under perennial pasture has produced a significant increase in C_p for the 0-50 mm soil layer (Figure 4.1a) at all the sites excepting sites 1 (12 years under pasture), and 3 (5 years under pasture). The following are considered to be the reasons for these restoration failures: site 1 is located on a steep slope (10%) on which there will inevitably have been much runoff and therefore a relatively droughty soil water regime; soil surface features reveal that some erosion occurred while the land was under cultivation (slopes like this should generally never be cultivated for annual crops on these soils in South Africa since 7% is considered an approximate threshold value); levels of P and Ca are low, and of Mg medium; no fertilizer applications were made; the poor grass sward density, rated as 2, (i.e. sparse), confirms poor growing conditions; as far as management is concerned it is relevant that this pasture has in fact been turned into a game camp. With all these disadvantages it is not surprising that the C gain at site 1 has only been 0.34 Mg ha^{-1} yr^{-1} over the 12 years that the land has been under pasture. In contrast site 3 is a well managed pasture where tall fescue is grown for seed; the grass cover is dense (rated as 5); status of P is low but that of Ca, Mg and K is high. The low rate of C restoration (0.1 Mg ha^{-1} yr^{-1}) is possibly due to excessive leaching of N due to the high annual water application (1020 mm) caused by rainfall plus irrigation at $\pm$300 mm per year; this contention is supported by the relatively low total N contents of the 0-100 mm soil layer, i.e. 759 mg kg^{-1} for the 0-50 mm of layer, compared to a mean for all sites of 1180 mg kg^{-1}, and 633 mg kg^{-1} for the 50-100 mm layer compared to the mean for all sites of 674 mg kg^{-1}. The complete annual removal at site 3 of vegetative material by mowing could also have retarded C gains.

In the 50-100 mm layer (Figure 4.1b) only the C_p values at sites 2 and 8 are significantly higher than C_e. The total C gain in Mg ha^{-1} yr^{-1}at these two sites (Table 4.1) is far higher than at the other sites, as are the estimated amounts of N available for growth. The slowness of C restoration in deeper layers of the previously ploughed layer is clearly revealed by these results, as is the importance of selecting appropriate sampling depths for studies of this kind.

Table 4.1 Characteristics of the sites in the Harrismith agro-ecosystem considered important for C sequestration, and the estimated annual C gains per hectare at each site. Meaning of abbreviations as defined in the beginning of the dissertation.

Site	Years under pasture	GSD	Slope (%)	Clay (%)	Nutrient levels*				MARP (mm)	Estimated N available (mg kg^{-1})	Total C gains (Mg $ha^{-1}yr^{-1}$)
					P	Ca	Mg	K			
1	12	2	10	13.2	L	L	M	H	637	19.5	0.33
2	14	5	0.5	16.6	M/L	L	M	L	652	26.0	1.33
3	5	5	4	11.5	L	H	H	H	1020	19.6	0.10
4	7	5	2	12.4	M	L	M	H	676	18.9	0.59
5	15	3	4	11.3	L	L	L	M	652	21.5	0.45
6	15	2	1	12.8	M	M	M	H	652	19.9	0.28
7	25	3	3.5	13.5	L	L	M	L	642	20.0	0.35
8	6	4	3.5	11.5	M	M	M	H	707	23.3	1.62

*L = low, M = medium and H = high

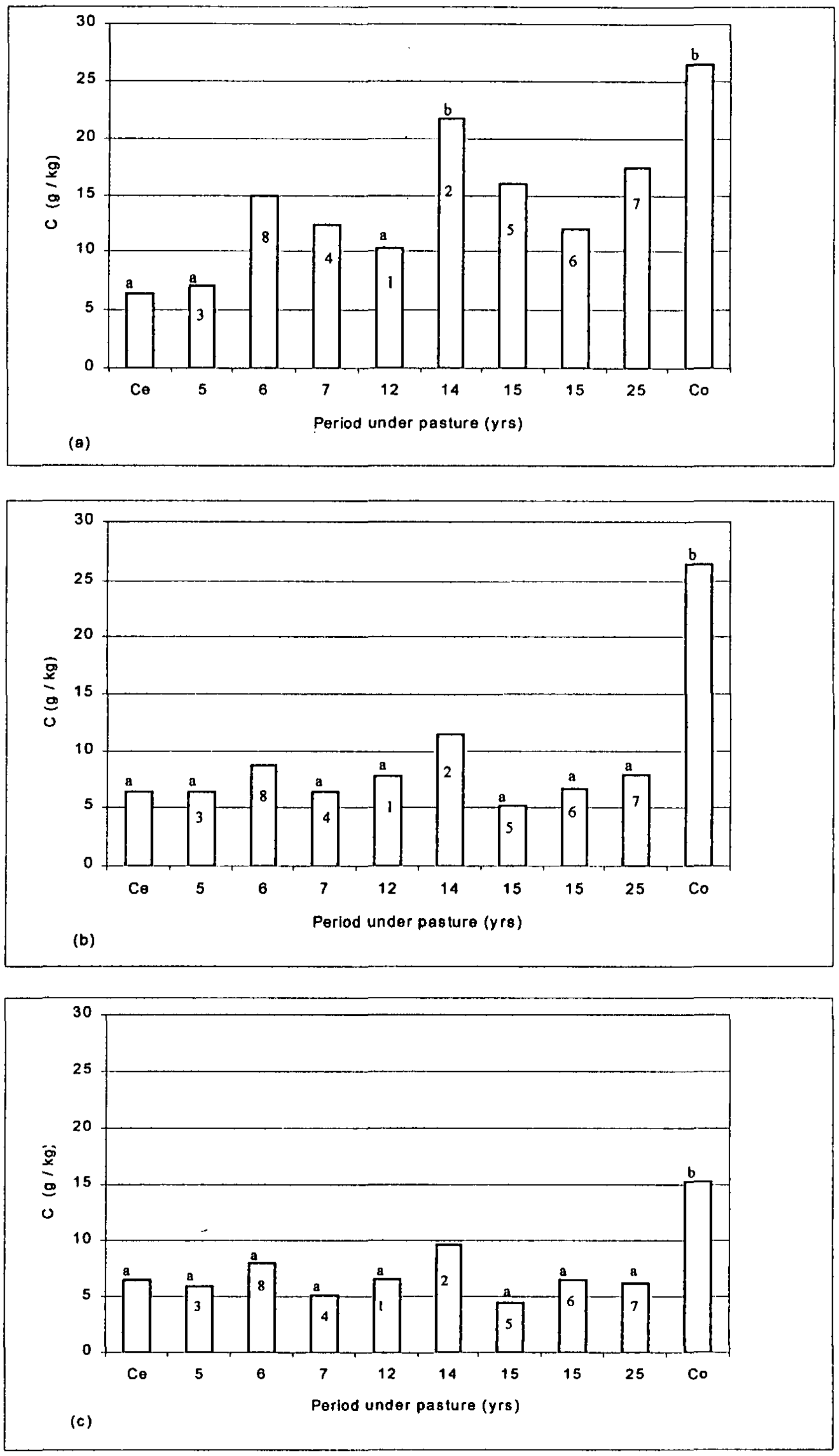


Figure 4.1 Organic carbon contents in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Harrismith agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 2.59, 0.88 and 0.85 for figures a, b and c respectively.

In the 100-200 mm layer (Figure 4.1c) it is only at site 2 that the C content is significantly higher than C_e, with site 8 nearly significant. Site 2 is clearly a site at which conditions are very favorable for C sequestration. It has the advantage over site 8 of having had more than double the number of years (14 compared to 6 years) to store C in the root zone.

4.2.1.1.2 Comparing C_p with C_0

When making this comparison it is necessary to keep in mind that the C_0 value presented in Figures 4.1a and 4.1b is the value obtained by Lobe *et al.* (2001) for the 0-100 mm layer (see the relevant comment under Section 4.1) The true C_0 values for the 0-50 and 50-100 mm layers is expected to be considerably higher than the 26.5 g kg^{-1} shown in Figure 4.1a, and lower than the 26.5 g kg^{-1} shown in Figure 4.1b. In the 0-50 mm layer (Figure 4.1a) it is only at site 2 that the C content is not significantly lower than C_0, indicating that at this favorable site after 14 years under pasture the C content in the 0-50 mm layer is approaching that of the mean value of the 0-100 mm layer for virgin soils in the Harrismith agro-ecosystem. In the deeper parts of the old plough layer (50-100 and 100-200 mm) all C_p values are significantly lower than C_0. The process of C restoration clearly starts from the top and progressively moves downwards.

4.2.1.1.3 Inter-site comparisons of C_p

At site 3, C_p in the 0-50 mm layer (Figure 4.1a) is significantly lower than at all the other sites. The next lowest C_p content in this layer is at site 1 which is significantly lower than at all the other sites excepting site 6. The disadvantages for C sequestration at sites 1 and 3 have already been described in Section 4.2.1.1.1. Site 6 has the following unfavorable features which are considered to have limited efficient C sequestration: the soil is shallow with the depth to the soft plinthic B horizon of only 400 mm, compared to 600 mm at all the other sites, and the grass sward density is rated as only 2 (Table 3.2).

The next highest C_p is at site 4. It is not significantly different from that of site 8 but significantly lower than that of sites 2, 5 and 7. In terms of C sequestration per annum, site 4 after only 7 years under pasture, has performed well giving the third highest value of 0.59 Mg ha^{-1} yr^{-1} (Table 4.1). This result is supported by the following observations: the grass sward density was rated as very high; the clay content is favorable; and the N and P fertility levels are satisfactory. The higher C_p values at sites 2, 5 and 7 are all largely due to the longer periods under pasture, i.e. 14, 15 and 25 years respectively.

The C_p at site 8 is not significantly different from that at sites 5 and 7 but significantly less than that at site 2. Site 8 was located in a pasture that visually gave the impression of being well cared for. All the information in Table 4.1 supports this conclusion; the grass sward density is high, the slope is gentle, the clay content is approximately in the middle of the range, and the N and P fertility levels are relatively high. The above average C content in relation to the restoration period of 6 years (Figure 4.1a), and the high overall C gain of 1.62 Mg ha^{-1} yr^{-1}, is therefore not unexpected. If the restoration curve is sigmoidal, as suggested by the results and research comments presented in the literature review, then this site may have the additional advantage of being located on a part of the curve that is fairly steep, i.e. where the annual C increments are relatively large. Flattening out of the restoration curve after the first decade under pasture, as suggested by Bruce *et al.* (1999), would help to explain the considerably lower C gains per year at site 2 compared to site 8.

The next highest C_p values are at sites 5 and 7 which are not significantly different from each other in spite of the latter having been under pasture for 10 years longer than the former. Conditions for C sequestration seem to be similar at those two sites. The grass sward density index at both was rated as 3 (moderately dense); both have moderate slopes (3.5-4.0%), and satisfactory clay contents; both are low in P and K, and have satisfactory N availability values; at both sites the pasture has been used for grazing and /or hay. Site 5 was burnt each spring during the last five years of the restoration period, and there were indications at site 7 that it had also sometimes been burnt. Burning is expected to retard C restoration by destroying all the old dead grass accumulated on the surface at the end of the previous growing season. The C_p at both sites is significantly less than that at site 2.

The greatest annual C gains occurred at sites 2 and 8 with values of 1.33 and 1.62 Mg ha^{-1} yr^{-1} respectively. These are far higher than the 0.8 Mg ha^{-1} yr^{-1} estimated by Bruce *et al.*(1999) for the United States of America and Canada for the first decade of the restoration period, and $\pm$ 75% of that for the second decade. It is relevant to note here that Potter *et al.*(1998) expects C sequestration rates to decline with increasing mean annual temperatures. The mean annual temperatures of the agro-ecosystems in this study will probably generally be higher than in the two countries referred to.

Site 2 seems to be situated in a region where conditions for C sequestration are considerably more favorable than for the other sites. It is situated opposite a gap between two elevated areas at the top edge of the Drakensberg escarpment, ideally suited to receive a higher rainfall than the region further away from the escarpment. Both Du Toit *et al.* (1994) and Lobe *et al.* (2001) took samples at sites less than 2 km away. They reported C_0 values of 23.2 and 28.3 g kg^{-1} respectively in the 0-200 mm soil layer. These are far higher than the mean values of 17.6 and 20.6 g kg^{-1} in the 0-200 mm layer respectively reported in Table 2.2 for their Harrismith sites. The C contents of the 0-100 mm layer at the site sampled by Lobe *et al.* (2001) was 33.7 g kg^{-1}. The high values cannot be ascribed to high clay contents as these are well within the average range at both sites, i.e. 15.7% for the site of Du Toit *et al.* (1994) and 14% for the site of Lobe *et al.* (2001). These results provide reliable evidence that conditions at site 2 are not representative of the average in the Harrismith agro-ecosystem. Other advantages for C sequestration at site 2 are a very gentle slope (0.05%), an above average clay content (16.6%), and a far higher total N content in the soil (Figure 4.2a) from which it is estimated that the concentration of N available to the pasture would be 26.0 mg kg^{-1}, compared to the equivalent average for the other sites of 20.4 mg kg^{-1} (Table 4.1). These are high values compared to the approximate threshold N fertility value of 15 mg kg^{-1} presented in Table 3.1.

The lowest C_p value in the 50-100 mm layer is at site 5 which is significantly lower than all the others (Figure 4.1b). It is also lower than C_e, in spite of the site having been under pasture for 15 years. The low value may be due to the fact that during the last five years the pasture was burnt every spring, thus every year destroying all dead organic material accumulated on the soil surface. The next group of low C_p values includes sites 3, 4 and 6 which are not significantly different from each other, but significantly lower than all the other higher values. The low C_p values at sites 3 and 4 are not surprising in view of the relatively short periods under pasture, viz. 5 and 7 years respectively. In contrast the relatively long restoration period of 15 years at site 6 has produced disappointing results. The influence of the low grass sward density (Table 4.1) is clearly exposed.

The next highest group of C_p values are at sites 1 and 7 with similar values not significantly different from each other, but significantly less than the C_p values at sites 2 and 8. Reasons for the relatively low C_p at site 7 after 25 years have already been described; burning may well be the most important one. The steep slope, low P status and eroded topsoil at site 1 have probably limited C sequestration there.

The next highest C_p is at site 8, which is significantly less than that at site 2. At both these sites conditions for C sequestration are clearly very favorable as already described in the discussion on the 0-50 mm layer.

Very little C has been stored in the 100-200 mm layer at most of the sites, even after periods of 15 and 25 years under pasture (Figure 4.1c). The ascending order of C content is similar to that for the 50-100 mm layer, and the possible reasons suggested for that layer and for the 0-50 mm layer regarding the reaction at each site, are also relevant here. The lowest C_p is at site 5, which is significantly lower than all the others excepting for that at site 4. However, the C_p at site 4 is not significantly different from that at site 3 but significantly less than all the others. The C_p values at sites 1, 3, 6 and 7 are not significantly different from each other but all are significantly less than that at sites 2 and 8. At site 8 the C_p is significantly less than site 2.

4.2.1.2 Total nitrogen

4.2.1.2.1 Comparing N_p with N_e

Results of this comparison are presented in Figure 4.2. In the 0-50 mm layer only N_p at site 3 is not significantly different from N_e. The overall pattern is therefore very similar to C, the only difference being that N_p at site 1 is significantly different here from N_e, whereas C_p at site 1 is not significantly different from C_e. In the 50-100 mm layer the pattern is the same as for C with only sites 2 and 8 having a significantly higher N_p than N_e. In the 100-200 mm layer only

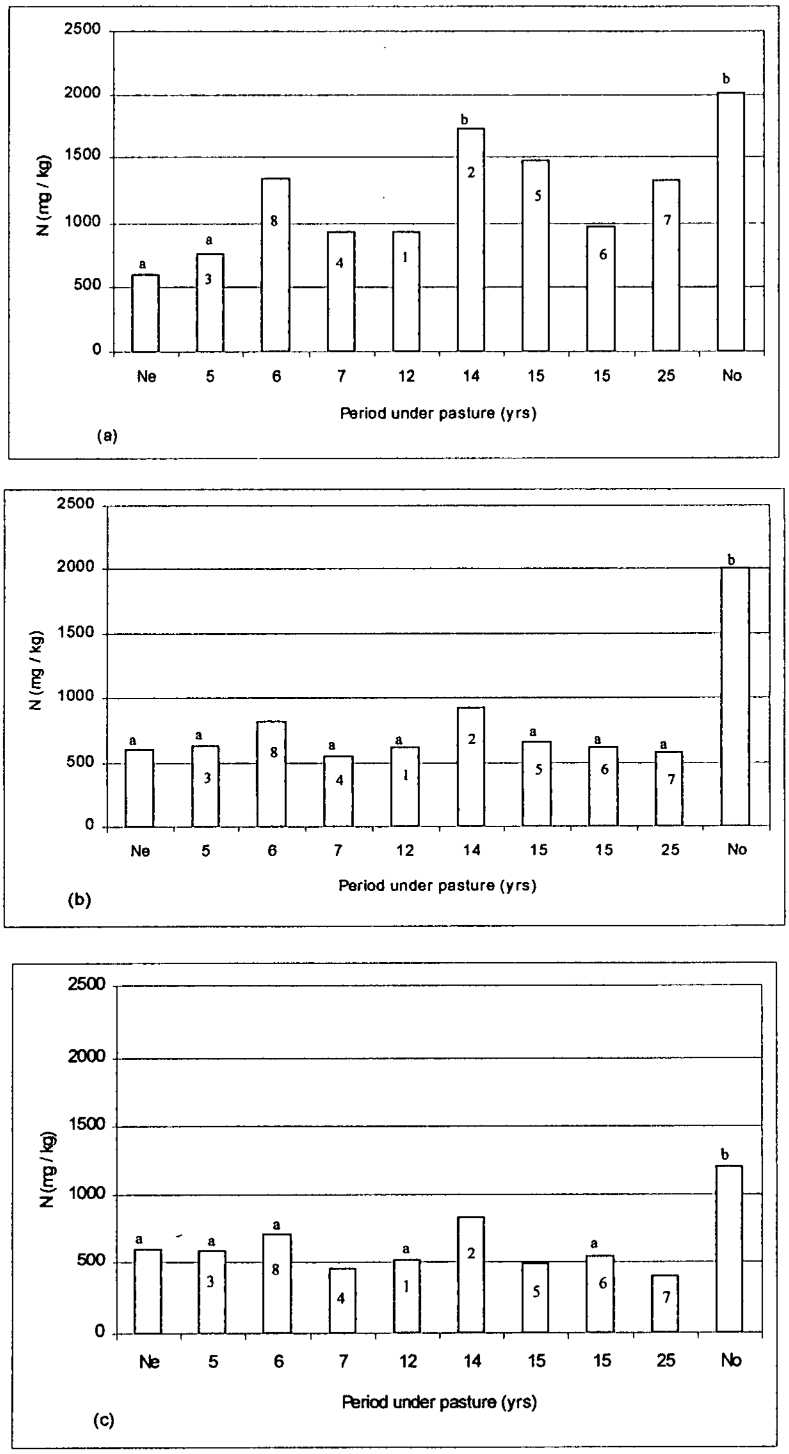


Figure 4.2 Total nitrogen contents in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Harrismith agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 158, 62 and 51 for figures a, b and c respectively.

N_p at site 2 is significantly higher than N_e. At all the other sites N_p is either lower than N_e or not significantly higher. This is also a very similar pattern to that of C.

4.2.1.2.2 Comparing N_p with N_0

In the 0-50 mm layer it is only at site 2 that N_p is not significantly different from N_0 (Figure 4.2a), therefore repeating the C pattern. Reasons are proposed in Section 4.2.1.1.2 for the high organic matter content at site 2. In the 50-100 and 100-200 mm layers all N_p values are significantly lower than N_0 (Figures 4.2b and 4.2c). Here again the pattern is similar to that of C.

4.2.1.2.3 Inter-site comparisons of N_p

In the 0-50 mm layer (Figure 4.2a) the ascending order of N_p is very similar to that of C_p. At site 3 N_p is the lowest. It is followed by sites 1, 4 and 6 with similar N_p values. The next group of sites with similar values is 5, 7 and 8. At site 2 N_p is the highest which is significantly different from all the others. The reasons proposed in Section 4.2.1.1.3 for C_p at each site apply equally here.

In the 50-100 mm layer (Figure 4.2a) the ascending order of N_p is as follows: the lowest values are at sites 1, 4 and 7, not significantly different from each other; the next lowest group is sites 3, 5 and 6, all significantly lower than site 8; the highest value is again at site 2 which is significantly higher than all the others. The pattern here is noticeably different from that of C_p for sites 3, 5 and 7. The annual burning during the last 5 years at site 5 seems to have had a greater detrimental influence on C sequestration than on N accumulation. Although some of the N contained in the vegetative material destroyed each year could have been lost to the atmosphere by volatilization, it was probably less than the C lost on ignition. Site 5 had the lowest C_p in both the 50-100 and 100-200 mm layers, whereas its N_p is the third highest in the 50-100 mm layer, and sixth highest in the 100-200 mm layer. The reason for the relatively low N_p compared to the C_p at site 7 is not clear. At site 3 the additional water received by irrigation may be the cause of the improved N_p values in the 50-100 and 100-200 mm layers compared to the C_p values. As relatively large N fertilizer applications were made on this irrigated pasture (Table 3.2), it is possible that some nitrate leaching occurred, augmenting the N content of the two lower layers.

In the 100-200 mm layer (Figure 4.2c) N_p is the lowest at site 7, significantly lower than at all the other sites, as well as being significantly lower than N_e. This is a surprising result from a 25 year old pasture. Signs of burning were seen at the time of sampling, although burning was not one of the regular management practices indicated by the farmer. The C_p of this layer is also unexpectedly low and not significantly different from C_e (Figure 4.1c). No reasonable explanation is available for these observations. The next highest group in ascending order of N_p is sites 4 and 5 (both significantly higher than site 7); it is followed by sites 1 and 6, then by site 3, with site 8 again significantly higher than all the other sites with lower N_p values. Site 2 has a significantly higher N_p than site 8. Possible reasons for the changed pattern of N compared to C_p accumulation at sites 3 and 5 have already been given. For the other sites the pattern is similar to C and the reasons given in Section 4.2.1.1.3 are therefore relevant.

4.2.1.3 C:N ratios

Results for the C:N ratios are presented in Figure 4.3. In the 0-50 mm layer the values for the sites are in all cases not significantly different from C_e:N_e, or C_0:N_0. This is not unexpected as the tendency for C:N ratios to remain constant is well known. The mean value for the sites is 11.8, very close to the mean for C_e:N_e and C_0:N_0 with values of 10.7 and 13.2 respectively.

In the 50-100 and 100-200 mm layers the ratios are fairly constant at most of the sites. The outlier values are those at sites 5 and 7, due possibly to burning in the case of site 5. The mean C:N ratios for these two deeper layers over the 8 sites are 11.3 and 11.7, respectively, showing a marked consistency over the three depths.

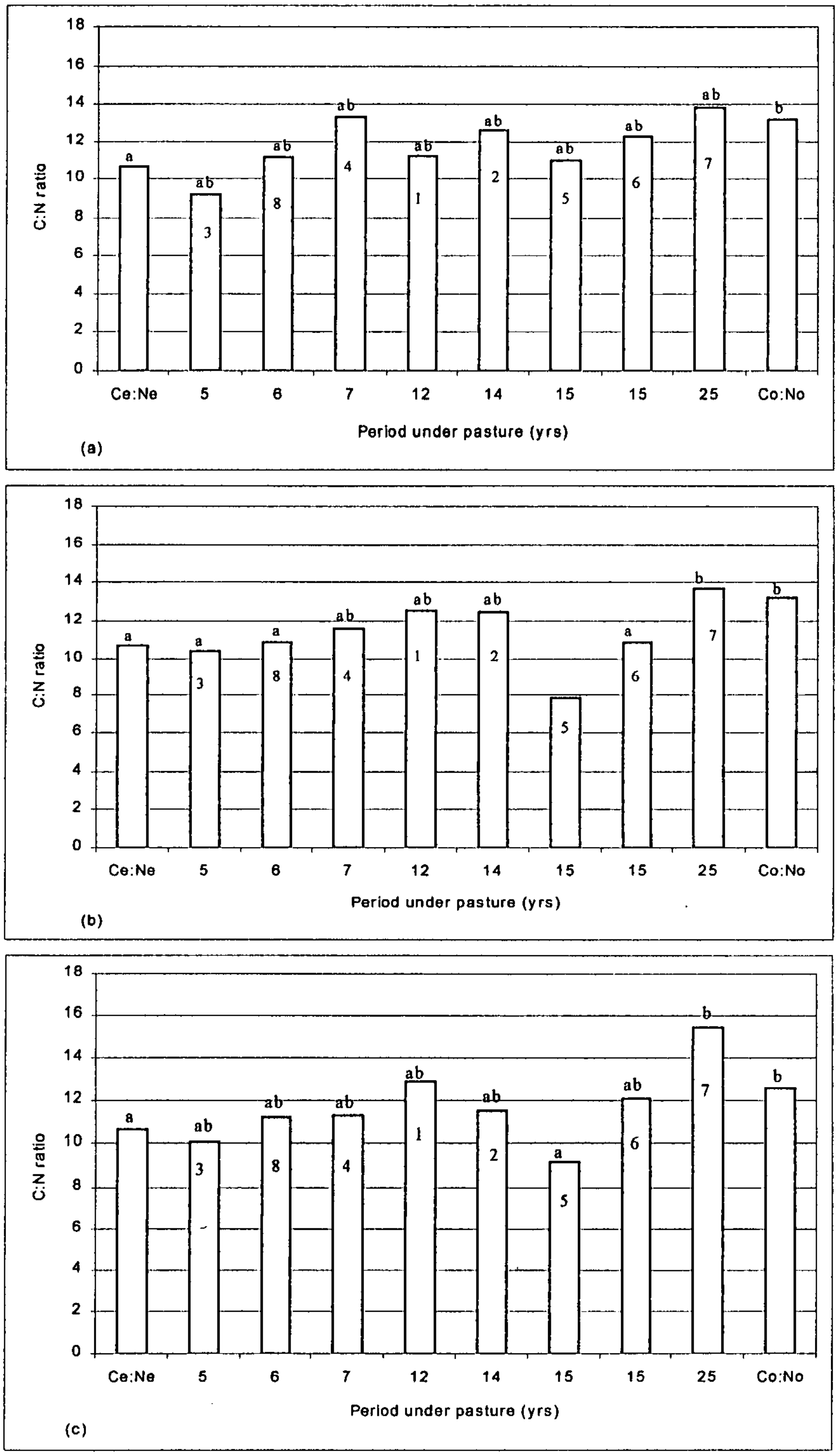


Figure 4.3 Carbon to nitrogen ratios in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Harrismith agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 3.24, 1.25 and 1.86 for figures a, b and c respectively.

4.2.2 Tweespruit agro-ecosystem

4.2.2.1 Organic carbon

4.2.2.1.1 Comparing C_p with C_e.

Important features of each site are presented in Table 4.2, and the C contents at the different sites are presented in Figure 4.4.

Restoration under perennial pastures resulted in a significant increase in C_p for the 0-50 mm layer at most sites excepting at sites 2, 3 and 4 (Figure 4.4a). It is important to note that the pastures at these sites never received any N fertilizer (Table 3.6).

Site 3 has the lowest C_p, even lower than C_e but not significantly so. The characteristics of the site recorded in Table 4.2 are all satisfactory excepting for the grass sward density, judged to be moderate, and the estimated N fertility level of 11.5 mg kg^{-1} which is below optimum according to the criteria presented in Table 3.4. It is also significant to note that the N_e value for Tweespruit recorded in Table 2.3 (combined data of Du Toit *et al.* 1994 and Lobe *et al.* 2001), is 518 mg kg^{-1}. Assuming a N mineralization rate of 3%, and according to the procedure used for the N fertility estimates in Table 4.2, the estimated N fertility level in the 0-200 mm layer after a long period of continuous cultivation on these soils can be expected to have been around 15 mg kg^{-1}. The fact that even after seven years under pasture the estimated N fertility level at site 3 is still below this value is reliable evidence that at establishment the level must have been even lower. It seems therefore that comments in the literature review in relation to the work of Theron & Haylett (1953) about a possible threshold N fertility level below which C restoration will be impaired, are relevant here. Theron & Haylett (1953) obtained no improved C restoration after 6 years under pasture when applying 57 kg N ha^{-1} yr^{-1} to a degraded soil, which they considered to have had a N content of 1050 mg kg^{-1} in the 0-300 mm layer at the start of the experiment. It is therefore reasonable to conclude that the mineralized N in their control plot supplied sufficient N for the C sequestration process to proceed unhindered. Assuming a mineralization rate of 3% the N fertility level would have

Table 4.2 Characteristics of the sites in the Tweespruit agro-ecosystem considered important for C sequestration, and the estimated annual C gains per hectare at each site. Meaning of abbreviations as defined in the beginning of the dissertation.

Site	Years under pasture	GSD	Slope (%)	Clay (%)	Nutrient levels*				MARP (mm)	Estimated N available (mg kg^{-1})	Total C gains (Mg $ha^{-1}yr^{-1}$)
					P	Ca	Mg	K			
1	11	2	2	12.9	M	M	M	H	616	16.2	0.3010
2	10	4	2.5	12.3	M	H	H	H	623	14.8	0.1386
3	7	3	0.5	10.4	H	H	M	H	686	11.5	0.0000
4	9	4	3	11.6	H	H	M	H	642	15.4	0.0824
5	14	3	1.5	8.6	M	H	M	H	693	15.8	0.2795
6	25	5	3	12.6	H	M	M	H	688	18.5	0.2968
7	8	5	1	9.5	H	M	M	H	663	13.5	0.2389
8	5	3	1.6	15.5	H	H	H	H	741	16.2	0.8582

*L = low, M = medium and H = high

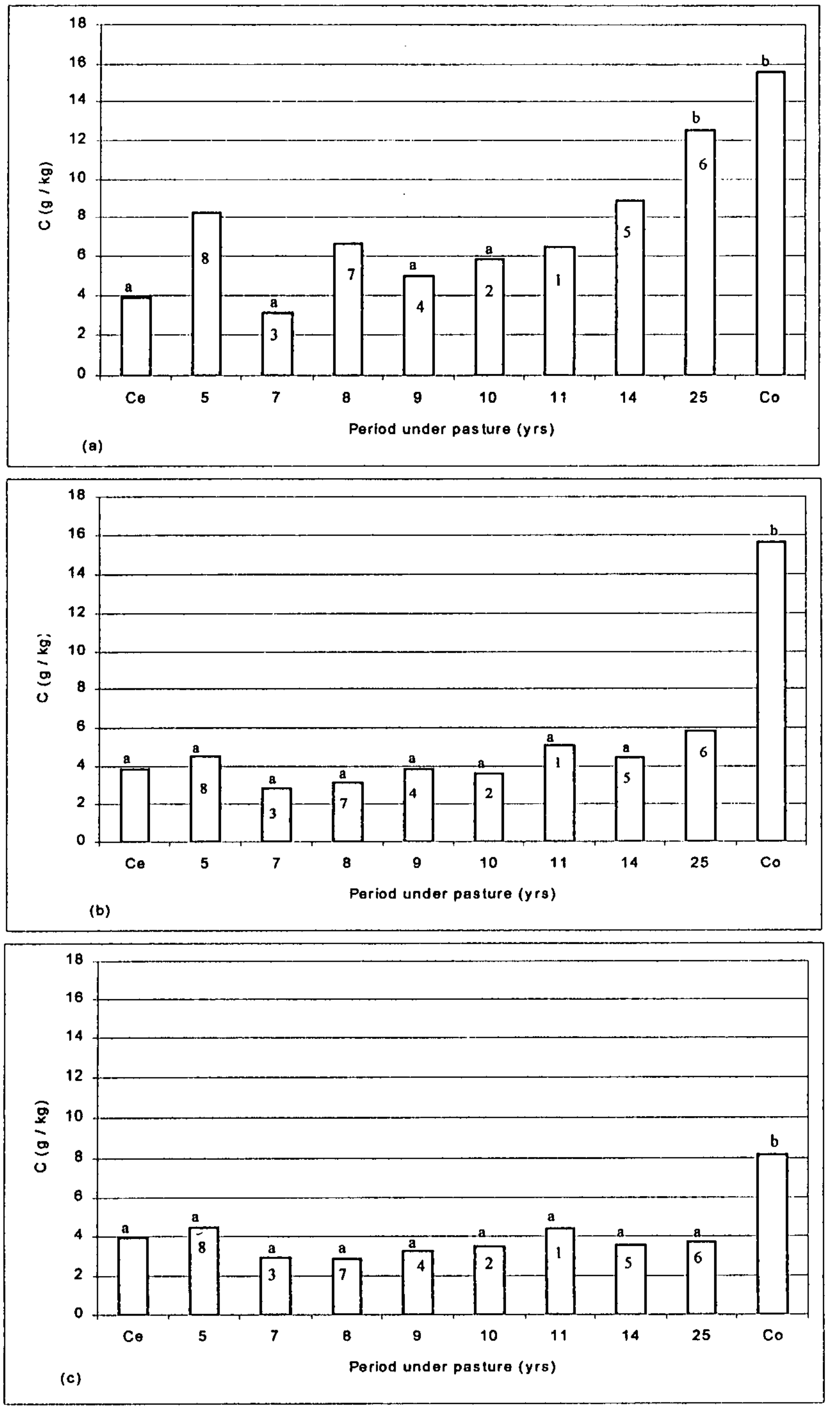


Figure 4.4 Organic carbon contents in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Tweespruit agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 1.07, 0.65 and 0.64 for figures a, b and c respectively.

been 32 mg kg^{-1}. It therefore seems very likely that the estimated N fertility level value of 11.5 mg kg^{-1} at site 3 was too low to support efficient C sequestration. The relatively low C content in the 0-50 mm layer at sites 2 and 4 is therefore probably also due largely to N fertility levels being below the threshold value for efficient C sequestration without the application of N fertilizer. The other characteristics of these sites are satisfactory. The total C gains in Mg ha^{-1} yr^{-1} at sites 2, 3 and 4 are also far lower than at all the other sites.

In the 50-100 mm layer (Figure 4.4b) all C_p values excepting that of site 6 are not significantly different from C_e. Site 6 has the advantage over the others of having been under pasture for a much longer period. At all other sites the period under pasture has evidently been too short under the prevailing conditions for a significant amount of C accumulation to occur in the deeper layers. In the 100-200 mm layer (Figure 4.4c) no C_p values are significantly different from C_e.

4.2.2.1.2 Comparing C_p with C_0

In the 0-50 mm layer only at site 6 is C_p not significantly different from C_0 (Figure 4.4a). Site 6 has the following advantages: it has been under pasture for 25 years; it has received regular fertilization of 46 kg N ha^{-1} yr^{-1} (Table 3.6), which is also reflected in the relatively high N fertility level of 18.5 mg kg^{-1}(Table 4.2) and the dense grass sward density; P, Ca, Mg and K levels are all satisfactory.

In the 50-100 and 100-200 mm layers (Figures 4.4b and 4.4c) all C_p values are significantly lower than C_0. Therefore, although the C content of the 0-50 mm layer at site 6 is approaching the equilibrium value of virgin soil (C_0) after 25 years under pasture, restoration of the lower part of the plough layer is still at an early stage. The mean C content of the 0-200 mm layer at site 6 is 9.0 Mg C ha^{-1} compared to 33.1 Mg C ha^{-1} for virgin land. It seems therefore that at least 75 years under pasture under these conditions will be needed for complete restoration of the 0-200 mm layer to be achieved. Similar periods are reported in the literature review.

4.2.2.1.3 *Inter-site comparisons of C_p*

In the 0-50 mm layer site 3 has the lowest C_p value and significantly lower than all the other sites (Figure 4.4a). The next highest C_p values are at site 4 and then at site 2, which are not significantly different from each other. Suggested reasons for these three low values are given in Section 4.2.2.1.1. The next highest group of C_p values is at site 1 followed by site 7, not significantly different from each other, with site 1 significantly higher than site 4. Judging by the low sward density observed at site 1, the C content and particularly the total C gain rate, is surprisingly high compared to site 4 after a similar period under pasture. The characteristics of the two sites as described in Table 4.2 are similar, and both received no N fertilizer. Possible reasons for better C sequestration at site 1 are the slightly longer period under pasture, the slightly superior N fertility level, and the fact that it is situated just below a road where runoff may have caused a moister water regime than at site 4. In spite of a below average clay content (9.5%) and low N fertility level (13.5 mg kg^{-1}) the grass sward density was high at site 7 and C sequestration rate reasonably high (0.24 Mg ha^{-1} yr^{-1}).

Site 8 and then site 5 follow site 7 in the ascending order of C_p for the 0-50 mm layer, with the former two sites significantly higher than all the sites with lower values, and not significantly different from each other. Site 8 has the advantages of an above average clay content (Table 4.2), above average mean annual rainfall of 741 mm during the period under pasture, regular N fertilization, a high fertility level and a dense sward. The C content is high considering the five year age of the pasture, as is the annual C gain. It is far higher than at any other site. A considerable amount of old semi-decomposed maize stalks was noticed lying on the surface between the tufts of grass. It seems that the maize stower was left on the land after the last maize crop had been reaped. This would have been beneficial, the surface mulch reducing water loss by evaporation and runoff, and supplying valuable nutrients. The main reason for the high C content at site 5 is probably the age of the pasture (14 years) coupled with the fact that it has received regular N fertilization (Table 3.6). Sequestration of C has occurred at an average rate at this site in spite of the below average clay content and relatively low sward density. The highest C content is at site 6. Reasons are presented in Section 4.2.2.1.2.

Very little C storage occurred in the 50-100 mm layer (Figure 4.4b) at most of the sites. Sites 1, 6 and 8 are exceptions. The reasons given for the C_p values in the 0-50 mm layer also apply here. The lowest C_p values are at sites 3, 7, 2 and 4, in this order. They are either equal to or lower than C_e. Next in ascending order are sites 5 and 8, not significantly different from each other and from site 4, but significantly higher than sites 2, 3 and 7. Then site 1 follows, not significantly higher than sites 5 and 8 but significantly higher than sites 2, 3 4 and 7. The highest C_p value is at site 6, which is significantly higher than all the other C_p values.

In the 100-200 mm layer (Figure 4.4c) C storage has been minimal. The lowest C_p values are again at sites 7, 3, 4 and 2, in this order, all less than C_e and not significantly different from each other. The next highest value is at site 5, which is significantly higher than that at site 7 but not significantly higher than that at sites 2, 3 and 4. The highest C_p values are at sites 1 and 8 which are significantly higher than all the others.

4.2.2.2 Total Nitrogen

4.2.2.2.1 Comparing N_p with N_e

The pattern in the 0-50 mm layer (Figure 4.5a) is very similar to that of C, excepting that here N_p at site 4 is significantly higher than N_e. The explanations about the different sites regarding C storage are therefore also applicable for N.

In the 50-100 mm layer (Figure 4.5b) the pattern is the same as for C. Only N_p at site 6 is significantly higher than N_e.

In the 100-200 mm layer N_p at sites 3 and 7 are significantly lower than N_e (Figure 4.5c), differing in this respect from the C pattern. The low N_p at site 3 is understandable in view of the comments made in Section 4.2.2.1.1 regarding this site. No logical explanation is available for the low N content at site 7, especially in view of the dense grass cover observed there (Table 4.2). All the other N_p values are not significantly different from N_e.

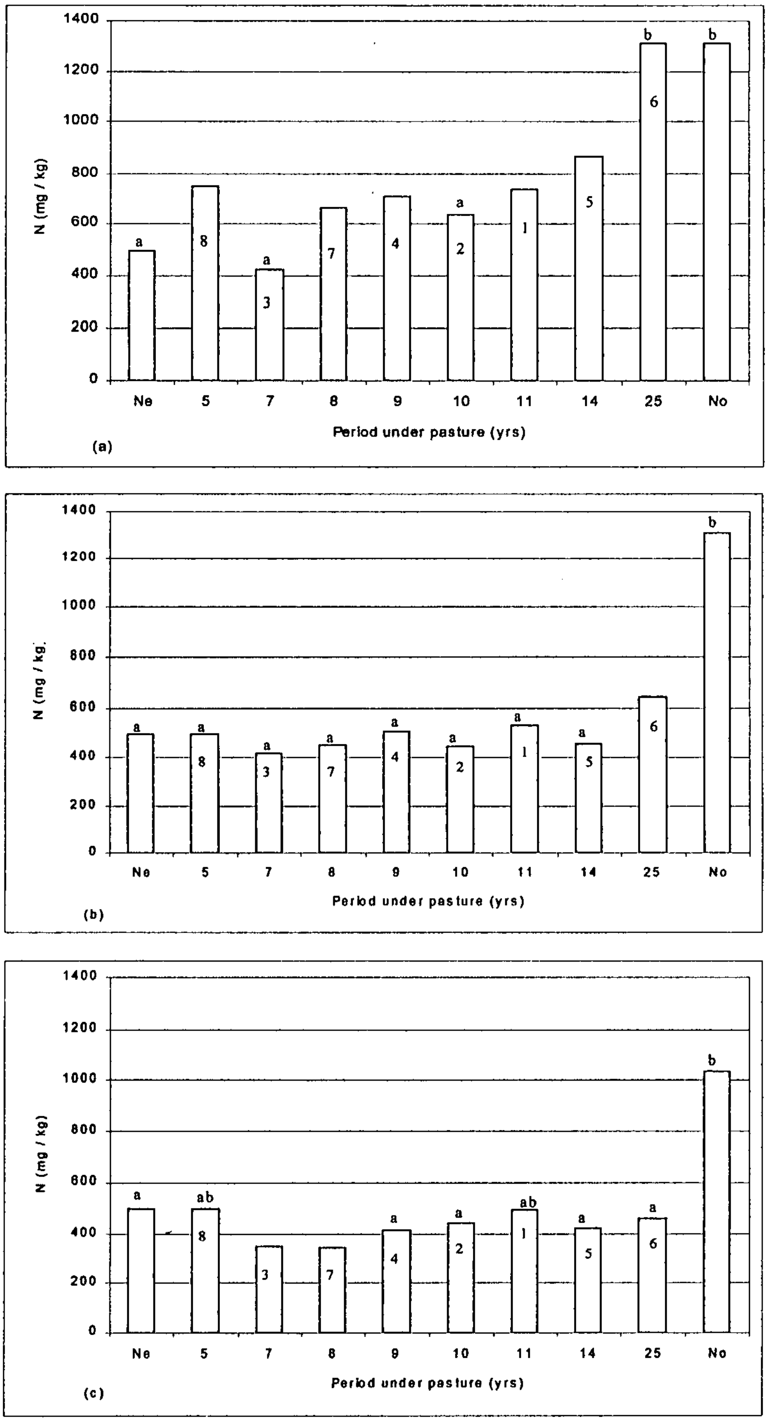


Figure 4.5 Total nitrogen contents in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Tweespruit agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 76, 59 and 64 for figures a, b and c respectively.

4.2.2.2.2 *Comparing N_p with N_0*

In the 0-50 mm layer (Figure 4.5a), as for C, only at site 6 is N_p not significantly lower than N_0. In the 50-100 and 100-200 mm layers (Figure 4.5b and 4.5c) the pattern is similar to that of C.

4.2.2.2.3 *Inter-site comparisons of N_p*

In the 0-50 mm layer N_p values, as for C_p, increase approximately in the order of increasing age of the pasture, with site 3 significantly lower than the other sites (Figure 4.5a), and site 6 significantly higher than the other sites. The 5 year old pasture at site 8 is out of order with a N_p similar to the 11 year old pasture at site 1. Possible reasons are given in Section 4.2.2.1.3. At all the sites where the period under pasture has been 14 years or less, N_p increases have been negligibly small in the 50-100 and 100-200 mm layers (Figure 4.5b and 4.5c), with the exception of site 6 with 25 year old pasture which is significantly higher in N_p than the 9, 10 and 14 year old pastures in the 100-200 mm layer. Delayed organic matter accumulation in the deeper layers is again displayed by these results.

4.2.2.3 C:N ratios

Results on the C:N ratios are presented in Figure 4.6. The patterns differ markedly in the three layers. In the deepest one (Figure 4.6c), where little organic matter accumulation has occurred, the C:N ratio remains fairly constant between 8 and 9, with no values significantly different from the 7.8 for C_e:N_e, or the 9.3 for C_0:N_0.

In the 0-50 mm layer (Figure 4.6a) the C:N ratio varies considerably between 7.1 at site 4 to 11.2 at site 8. The low values at sites 3 and 4 are those where annual C gains have been lowest (Table 4.2). The higher values, above 9, generally occur where annual C gains have been above 0.23 Mg ha^{-1} yr^{-1}, i.e. at sites 5, 6, 7 and 8. At these sites the C:N ratios are not significantly different from C_0:N_0. At all the sites the C:N ratios are not significantly different from C_e:N_e (Figure 4.6a).

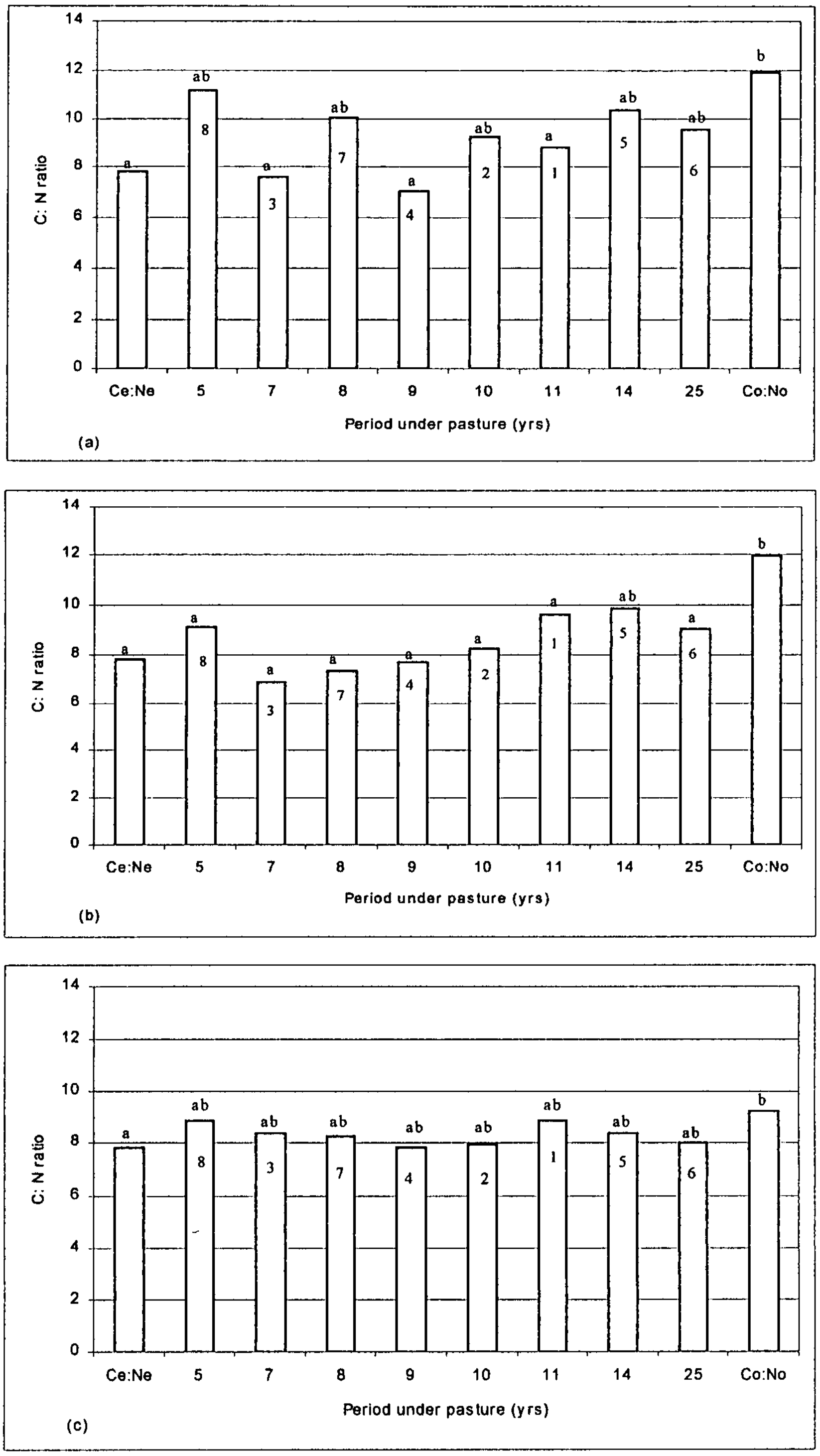


Figure 4.6 Carbon to nitrogen ratios in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Tweespruit agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 1.87, 1.28 and 0.80 for figures a, b and c respectively.

In the 50-100 mm layer (Figure 4.6b) the variation between sites is less than in the 0-50 mm layer but more than in the 100-200 mm layer (Figure 4.6c). At none of the sites is the C:N ratio significantly different from C_e:N_e, but all, excepting at site 5, are significantly lower than C_0:N_0.

4.2.3 Kroonstad agro-ecosystem

4.2.3.1 Organic carbon

4.2.3.1.1 Comparing C_p with C_e

Important characteristics of each site are summarized in Table 4.3, together with the total C gains during the restoration period. For the qualitative nutrient level assessment, threshold values were taken from Table 3.4. The C contents at the different sites and for the different layers are presented in Figure 4.7.

In the 0-50 mm layer the C_p values at sites 2, 4, 5 and 12 are not significantly different from C_e. The lowest C_p value is at site 2, which is only slightly higher than C_e, even after 17 years under pasture. The very low N fertility level and very low N fertilizer application (Table 3.9) are considered to be the main reasons for the poor grass sward density, low C content in all the layers, and resultant very low C gain rate in the 0-200 mm layer of only 0.04 Mg ha^{-1} yr^{-1} (Table 4.3) compared to the mean for the other sites of 0.58 Mg ha^{-1} yr^{-1}. If there is some threshold value of available N below which efficient C sequestration is impaired, then it seems that for the Kroonstad agro-ecosystem it may be around 11 mg kg^{-1}. Relatively low C_p values at sites 4 and 12 are to be expected as these pastures are only 4 and 5 years old respectively. Site 4 has the additional disadvantage of having a very low clay content of 7.3%, which is partly compensated for by the good depth of 900 mm to the soft plinthic B horizon (Table 3.9); it must also have had a low N content when the pasture was planted, judging by the very low estimated N fertility level of 10.3 mg kg^{-1}. The adequate annual application of 33 kg N ha^{-1} (Table 3.9), which would have provided an additional 12 mg kg^{-1} of N in the 0-200 mm layer, seems to have compensated for the low N fertility level judging by a satisfactory C

Table 4.3 Characteristics of the sites in the Kroonstad agro-ecosystem considered important for C sequestration, and the estimated annual C gains per hectare at each site. Meaning of abbreviations as defined in the beginning of the dissertation.

Site	Years under pasture	GSD	Slope (%)	Clay (%)	Nutrient levels*				MARP (mm)	Estimated N available (mg kg^{-1})	Total C gains (Mg $ha^{-1} yr^{-1}$)
					P	Ca	Mg	K			
1	20	5	1	8.8	H	M	M	H	557	15.7	0.4662
2	17	2	1.5	10.7	H	L	M	H	565	10.0	0.0424
3	8	3	< 0.5	14.3	H	H	M	H	589	16.8	0.7726
4	4	3	0.7	7.3	H	M	M	H	576	10.3	0.5705
5	10	3	2	11.7	M	H	H	H	564	12.9	0.4760
6	5	3	3	10.0	H	M	H	H	625	12.4	0.7714
7	9	3	1	10.5	H	M	H	H	573	12.6	0.5950
8	10	3.5	0.7	14.2	H	H	H	H	564	15.1	0.8379
9	8	2.5	0.7	7.7	H	L	M	H	589	11.7	0.5679
10	18	2	0.7	11.5	H	M	H	H	562	14.4	0.4787
11	18	3	1	11.5	M	M	M	H	562	13.5	0.3512
12	5	2	< 1	8.8	H	L	M	H	625	12.1	0.5264

*L = low, M = medium and H = high

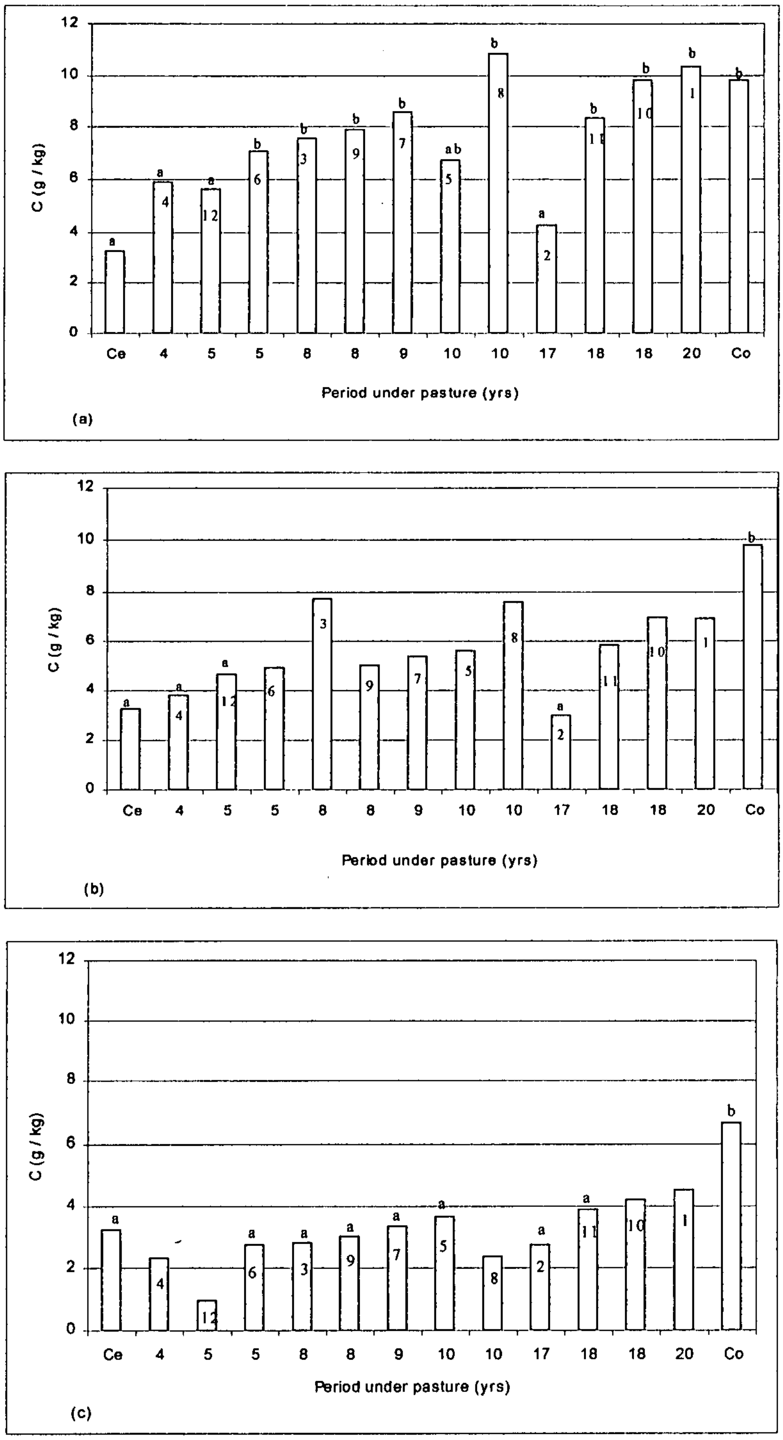


Figure 4.7 Organic carbon contents in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Kroonstad agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 1.84, 0.74 and 0.34 for figures a, b and c respectively.

sequestration rate of 0.57 Mg ha^{-1} yr^{-1} (Table 4.3). Site 12 has a number of disadvantages. The clay content of 8.8% is low; the N fertility level is low, and in addition the single N fertilizer application two years after planting (Table 3.9), if averaged out over the 5 years could only have provided around 3 mg kg^{-1} of available N; the soil belongs to the Westleigh form with only 350 mm above the soft plinthic B horizon and the soil is consequently shallower than at all the other sites. These disadvantages are expressed in the low grass sward density observed at the site. No good reason is available for the relatively low C_p at site 5 after 10 years under pasture.

In the 50-100 mm layer (Figure 4.7b) the C_p at sites 2, 4 and 12 are again the lowest and not significantly different from C_e, with the value at site 2 actually lower than C_e.

In the 100-200 mm layer (Figure 4.7c) the C_p at sites 2, 3, 6, 9, 5, 7 and 11 are not significantly different from C_e; the first four C_p values being lower than C_e, and the last three slightly higher than C_e. It has already been seen in the results for the Harrismith and Tweespruit agro-ecosystems that C storage starts in the 0-50 mm layer and moves down to the deeper layers later. This process has evidently also occurred here resulting in minimal C storage in the 100-200 mm layer at all sites where the age of the pasture is equal to or less than 10 years, i.e. at sites 3, 5, 6 and 9. There has evidently not been enough time at these sites for C storage to occur in this bottom part of the old plough layer, in spite of the C sequestration rate being satisfactory at around 0.5 Mg ha^{-1} yr^{-1} or higher. These remarks are not valid for site 11 with an 18 year old pasture. The reason for the low C_p there is probably the low N fertility level of 13.5 mg kg^{-1}, with no N fertilizer applications (Table 3.9) to promote growth. At sites 4, 8, and 12 C_p is significantly less than C_e. The low values at sites 4 and 12 are probably mainly due to the short period under pasture. All the characteristics of site 8 are favorable (Table 4.3), and it also has the highest C sequestration rate of 0.84 Mg ha^{-1} yr^{-1}, which compares favorably with a general restoration rate under perennial pasture of 0.8 Mg ha^{-1} yr^{-1} predicted by Bruce *et al.*(1999) for the United States of America and Canada. Storage of C seems, however, to have been concentrated in the 0-100 mm layer where site 8 has a higher average C_p after 10 years than the 18 year old (sites 10 and 11), and 20 year old (site 1) pastures (Figures 4.7a and 4.7b).

4.2.3.1.2 Comparing C_p with C_0

At all sites, excepting 2, 4, and 12, the C_p of the 0-50 mm layer (Figure 4.7a) is not significantly different from C_0. Included are six sites with pastures between 5 and 10 years old. This is a different pattern to that observed for the Harrismith and Tweespruit agro-ecosystems. Storage of C in the 0-50 mm layer has been considerably more efficient in the Kroonstad agro-ecosystem. In the 50-100 and 100-200 mm layers (Figure 4.7b and 4.7c), the pattern is radically different from the surface layer, with the C_p at all sites being significantly lower than C_0.

4.2.3.1.3 Inter-site comparisons of C_p

The lowest C_p values for the 0-50 mm layer (Figure 4.7a) in ascending order are at sites 2, 12 and 4 which are not significantly different from each other. The relevant characteristics of these sites have already been described in Section 4.2.3.1.1.

The next highest C_p values are at sites 5 and 6, not significantly different from each other or from the C_p values at sites 4 and 12, but significantly higher than the C_p value at site 2. The high C gain rate at site 6 of 0.77 Mg ha^{-1} yr^{-1}(Table 4.3) shows that conditions here are favorable for C sequestration. The relatively low value of C_p in the 0-50 mm layer is due to the young age of the pasture. Site 5 has no clearly discernable unfavorable characteristics, with the possible exception of a moderate P fertility level, compared to a high level at all the other sites, excepting site 11 where the C sequestration rate is also low. The N fertility level at site 5 seems to be satisfactory and in addition adequate N fertilizer applications have been made (Table 3.9). There is therefore no reasonable explanation for the relatively low C_p, especially when comparing it with site 6 which has a higher C_p on a pasture half the age, and with similar clay content, N fertility status and N fertilization. Unsatisfactory C sequestration at site 5 is also exposed when comparing it with site 8. Both pastures are 10 years old with site 5 receiving far more N fertilizer annually (Table 3.9). In spite of this the C sequestration rate at site 8 is almost double that at site 5.

The C_p value at site 3 is the next highest in the ascending order. It is not significantly higher than at sites 5 and 6, and not significantly lower than the following three sites in the ascending order, i.e. 9, 11, and 7. The high C gain rate of 0.77 Mg ha^{-1} yr^{-1} at site 3 indicates favorable conditions. Supporting evidence is the relatively high clay content, high P level, and high N fertility level of 16.8 mg kg^{-1}. Although no N fertilizer was applied the pasture evidently benefited a great deal by the presence of lucerne mixed with the grass. As the pastures at sites 3, 7 and 9 are of similar age (Figure 4.7), their C_p values can be meaningfully compared. Excluding site 2 the mean C gain rate for this agro-ecosystem is 0.58 Mg ha^{-1} yr^{-1}. The rates at sites 7 and 9 are close to this value, indicating "average" conditions for C sequestration. Disadvantages at site 9 are a low clay content (7.7%), a poor grass sward density, a relatively low N fertility level and a low level of N fertilization. The pasture at site 7 received the same N fertilization as at site 9, it had a slightly higher residual N fertility level, a slightly higher clay content and the advantage of being one year older; the slightly higher C_p is therefore understandable. The rate of C gain at site 11 is below average (Table 4.3), resulting in a lower C_p value in the 0-50 mm layer after 18 years than at site 7 after 9 years. Probable reasons are the lack of N fertilization, a relatively low N fertility level, and a slight P deficiency.

The pastures at sites 10, 1, and 8, in this order, have the highest C_p values. They are not significantly different from each other but are significantly higher than all the other values excepting the C_p value at site 7. The pastures at sites 10 and 1 are of similar age, viz. 18 and 20 years respectively, and have produced similar C gains. Although these values are slightly below average this may be partly due to the fact that the C gain curve probably starts to flatten out at around this age (Bruce *et al.*, 1999). Neither of these sites received N fertilizer (Table 3.9), but both had reasonably high residual N fertility levels and high P levels (Table 4.3). Disadvantages at the two sites are a low grass sward density at site 10 and a low clay content at site 1. Conditions for C sequestration at site 8 are evidently very favorable, resulting in a C_p value in the 0-50 mm layer greater than C_0, and the highest C gain rate of 0.84 Mg ha^{-1} yr^{-1}. Beneficial characteristics of the site are a relatively high clay content, high P level, relatively high N fertility level, and at least some regular N fertilization.

In the 50-100 mm layer (Figure 4.7b) the pattern is generally similar to the 0-50 mm layer with the prominent difference being the unusually high C_p value at site 3, which is significantly higher than all the others. This is presumably due to the pasture having lucerne mixed with it . The C_p values at sites 2, 4 and 12 are again the lowest with the value at site 2 significantly lower than that at site 4, which is in turn significantly lower than that at site 12. The next group consists of the C_p values at sites 5, 6, 7 and 9 not significantly different from each other, but all significantly higher than the values at sites 2 and 4. Site 11 again has an intermediate C_p significantly higher than the C_p values at sites 6, 7 and 9, and significantly less than the C_p at sites 1, 8 and 10.

Notable features in the 100-200 mm layer (Figure 4.7c) are the extremely low C_p value at site 12, and the unexpectedly low values at sites 3 and 8 compared to the 50-100 mm layer. The C_p at site 12 is less than one third of C_e and significantly lower than at all the other sites. The low clay content, shallow soil and young age of the pasture at this site seem to have had a far more severe influence on the C storage in this deeper layer than on the shallower layers. No reasonable explanation for the depressed C_p values at sites 3 and 8 is available. The C_p values at sites 4 and 8 are significantly lower than at all the other sites with the higher values. In the 100-200 mm layer the oldest pastures, i.e. at sites 1, 10 and 11, have the highest C_p values, significantly higher than all the other sites excepting site 5.

4.2.3.2 Total nitrogen

4.2.3.2.1 Comparing N_p with N_e

For the comparison N_p versus N_e of the 0-50 mm layer (Figure 4.8a), the results are almost exactly the same as for C. In the 50-100 mm layer (Figure 4.8b) the pattern is different from that of C, with a total of eight sites (2, 4, 5, 6, 7, 9, 11 and 12) having N_p values not significantly different from N_e, compared to only three sites (2, 4 and 12) in the case of C. In the 100-200 mm layer (Figure 4.8c) the patterns for C and N are again very similar.

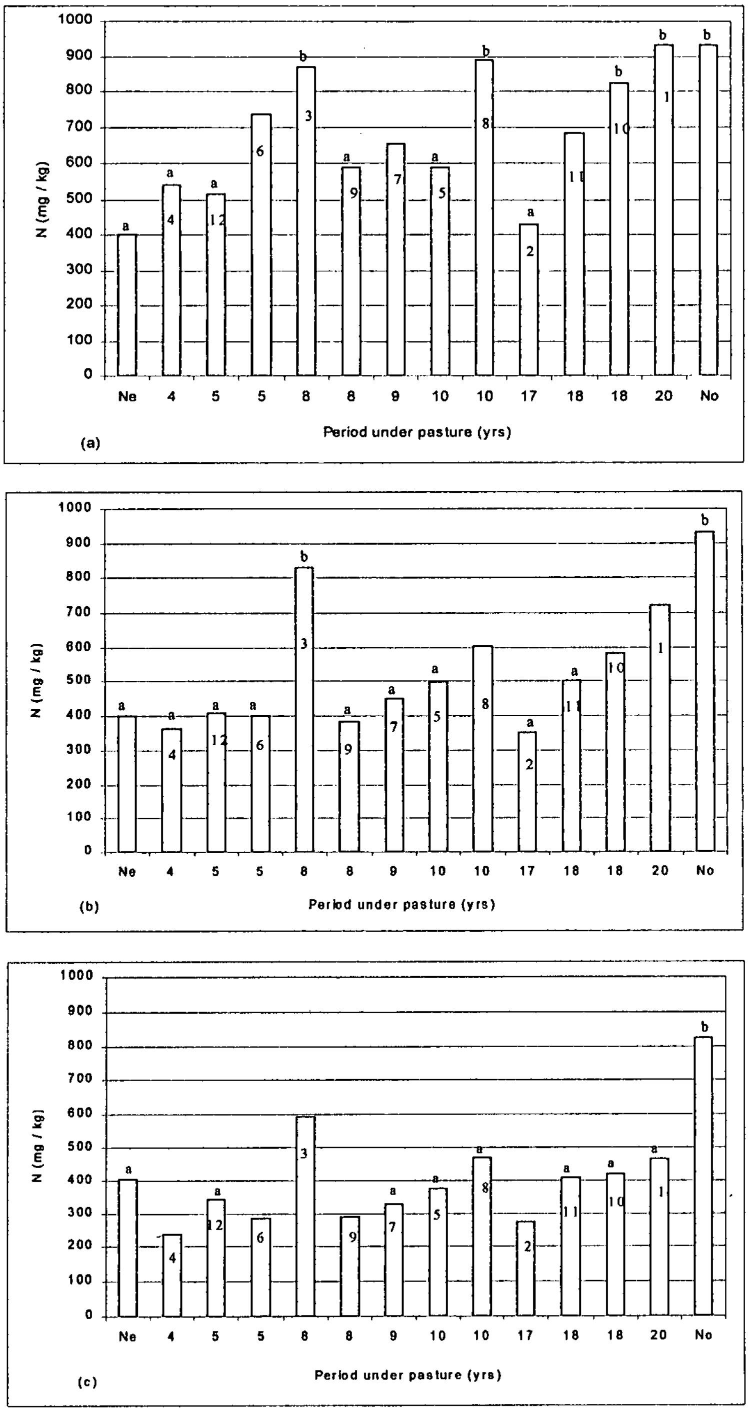


Figure 4.8 Total nitrogen contents in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Kroonstad agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 100, 56 and 39 for figures a, b and c respectively.

4.2.3.2.2 *Comparing N_p with N_0*

Comparing N_p values with N_0 for the 0-50 mm layer shows that the pattern is very different from that of C. Of the nine sites at which C_p values were not significantly different from C_0, only at four sites, i.e. 1, 3, 8 and 10, are N_e values not significantly lower than N_0. For the 50-100 and 100-200 mm layers the N_p versus N_0 comparisons yield very similar results to those of C_p versus C_0 (Figure 4.8).

4.2.3.2.3 *Inter-site comparisons of N_p*

The inter-site comparisons yield the following results. The most prominent feature in Figure 4.8 is the high N_p in all the layers at site 3, the only site with a legume mixed with the grass. The beneficial effects of the additional N provided by the lucerne on C sequestration is only clearly visible in the 50-100 mm layer (Figure 4.7b). The results in Figure 4.8 show that the N_p for the 0-50 mm layer at site 3 is not significantly lower than the two highest values at sites 1 and 8, and that in the 50-100 and 100-200 mm layers, site 3 has by far the highest N_p which is significantly higher than all the other values. Another notable feature of the N distribution pattern at the different sites, which is different from C, is the consistently high N_p value for all layers at site 8. The C content at site 8 is relatively very high in the 0-50 and 50-100 mm layers, but very low in the 100-200 mm layer. It may be significant that the clay contents at sites 3 and 8 are similar i.e. 14.3 and 14.2 % respectively and considerably above the average value of 10.6 % for the Kroonstad agro-ecosystem (Table 3.10). For all the other sites, as for C_p, the N_p values can be approximately divided in to three groups, viz. low, intermediate and high. The sites which occur in each of these groups of N_p values are approximately the same as for the equivalent groups of C_p values.

4.2.3.3 C:N ratios

In the 0-50 mm layer (Figure 4.9a) all values are higher than C_e:N_e and range from 8.7 to 13.7, with a mean of 11.3. Only at sites 7 and 9 are the C_p:N_p ratios significantly different from C_e:N_e (8.0) and C_0:N_0 (10.5). No reasonable explanation is available for this observation. In the 50-100 mm layer all values are again higher than C_e:N_e with the range and mean very

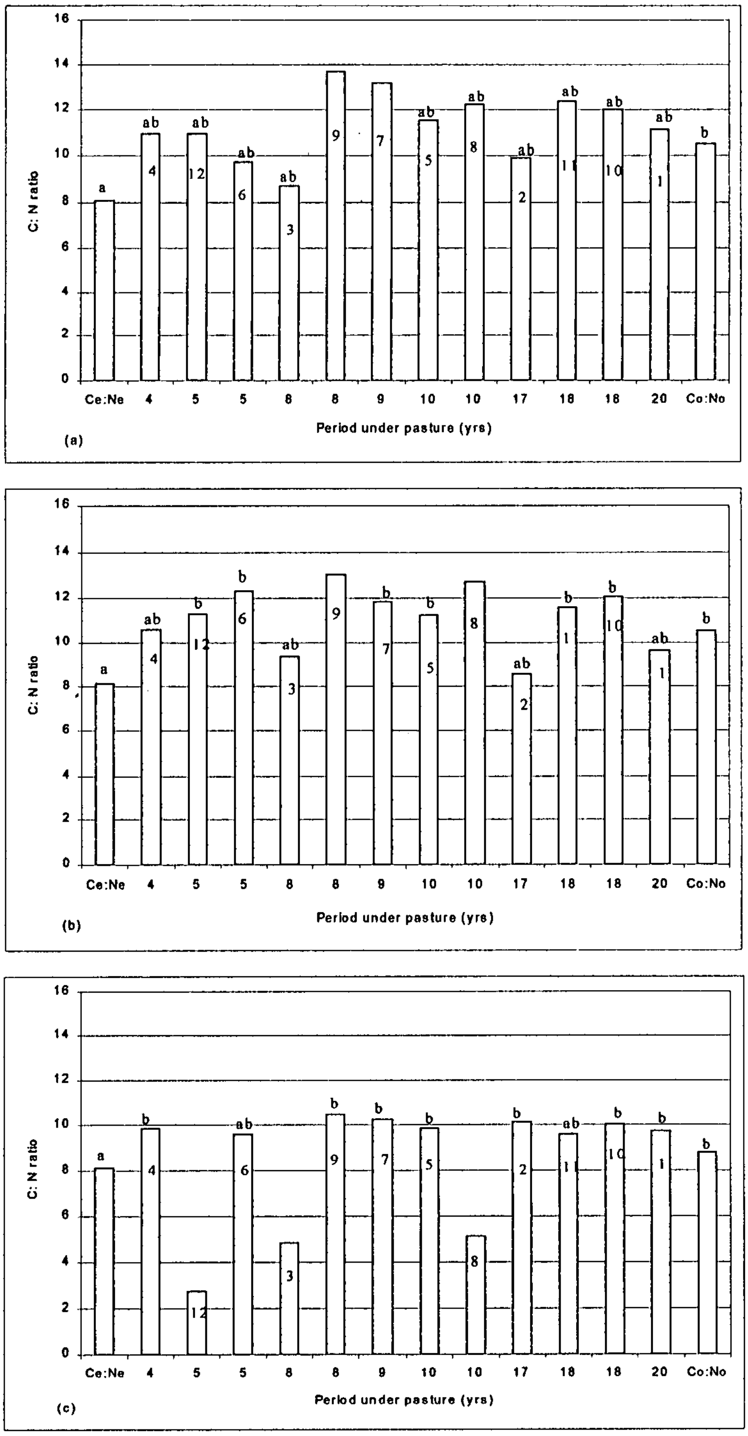


Figure 4.9 Carbon to nitrogen ratios in the 0-50 mm (a), 50-100 mm (b) and 100-200 mm (c) layers of the Kroonstad agro-ecosystem sites. The number recorded in the bar chart is the site number. Statistical results for the three sets of comparisons are presented as follows: for C_e versus C_p no significant difference is indicated by "a" at the top of the bars; for C_0 versus C_p no significant difference indicated by "b"; for inter-site comparisons LSD values are 2.40, 1.28 and 0.75 for figures a, b and c respectively.

similar to the 0-50 mm layer. The pattern in the 100-200 mm layer (Figure 4.9c) is different from the two shallower layers. The relatively high N_p values at sites 3 and 8, already discussed in Section 4.2.3.2, have given rise to very low C_p:N_p values of around 5 in the 100-200 mm layer at these sites. The lowest value of 2.8 is at site 12. An explanation is not available for this extremely low value. The mean of the remaining 9 values is 10.0, in all cases not significantly different from C_0:N_0, but in most cases significantly higher than C_e:N_e.

4.3 PATTERN OF ORGANIC MATTER RESTORATION WITH INCREASING TIME UNDER PERENNIAL PASTURE ON THE THREE AGRO-ECOSYSTEMS

In a world-wide framework all the sites investigated can be classed as coarse textured soils of the semi-arid South African savanna (Lobe *et al.*, 2001). An attempt has therefore been made to describe a common organic matter restoration pattern for the three agro-ecosystems, thus complementing the common degradation pattern described by Lobe *et al.* (2001). Selected sites were omitted from the study because of characteristics considered to be non-representative. Details of these sites are presented in Table 4.4.

A quadratic equation was used to describe the restoration curves displayed in Figures 4.10 to 4.13:

$$y = a + bx + cx^2 \qquad 4.1$$

Where y is either the C or N content of the soil and x the number of years the soil is under pasture. The a, b and c coefficients and correlation coefficient (r) for all the curves are presented in Table 4.5.

Table 4.4 Details regarding sites omitted from the restoration pattern study.

Agron-ecosystem	Site	Reason
Harrismith	2	Microclimate considered to be abnormally wet (details are given in Section 4.2.1.1.3)
	3	The only pasture in the study that was irrigated (details are given in Section 4.2.1.1.1).
Tweespruit	3	Because of the absence of any N fertilization the N fertility level was considered to be too low to support normal organic matter restoration (details are given in Section 4.2.2.1.1)
Kroonstad	2	The N fertility level considered too low to support normal organic matter restoration in the absence of adequate N fertilization (details are given in Section 4.2.3.1.1)
	3	The only pasture in the study which had a legume mixed with the grass, resulting in abnormally high N levels (details are given in Section 4.2.3.1.1)
	12	A shallow soil of the Westleigh form, the only one sampled in the Kroonstad agro-ecosystem (details are given in Section 4.2.3.1.1).

4.3.1 Organic carbon

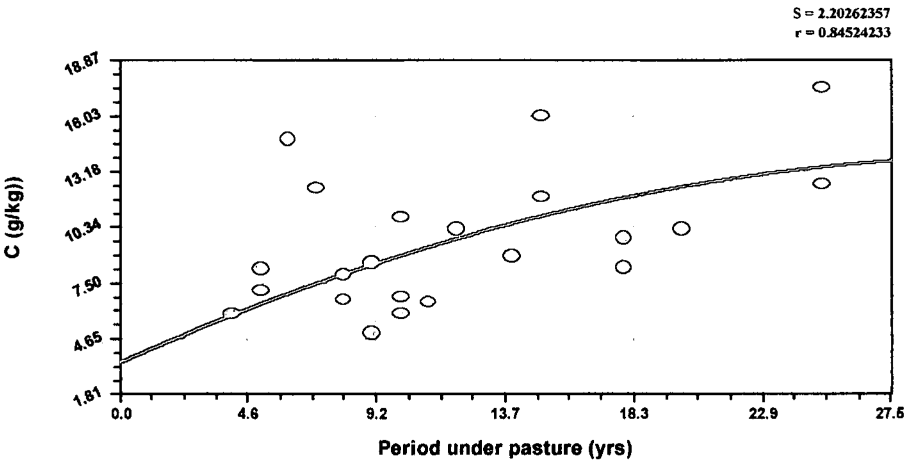
4.3.1.1 Absolute values

Results are presented in Figure 4.10. The curve was forced through 3.23 g kg $^{-1}$ at 0 years, the lowest C_e value for the three agro-ecosystems. There is only one C_e value for all depths since it has been assumed that after long cultivation the composition of the 0-200 mm plough layer will be reasonably homogeneous.

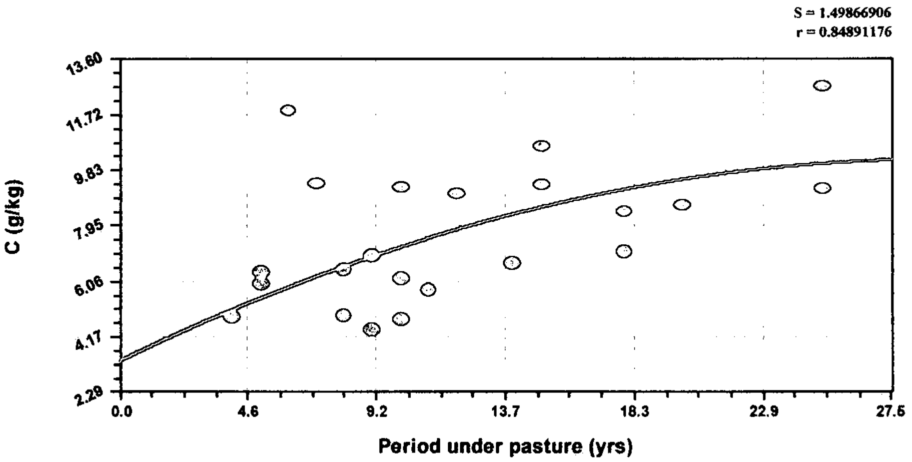
Table 4.5 Coefficients for the quadratic equations describing the curves in Figures 4.10, 4.11, 4.12 and 4.13, and the respective correlation coefficients (r).

Figure		Coefficients			
		a	b	c	r
4.10	a	3.4525	0.6432	-0.0098	0.8452
	b	3.3687	0.4662	-0.0079	0.8489
	c	3.3027	0.2859	-0.0048	0.7870
4.11	a	4.0442	13.5048	-0.2363	0.8776
	b	2.0832	9.1678	-0.1705	0.8213
	c	0.5594	4.2619	-0.0626	0.7806
4.12	a	417.9665	43.7901	-0.5180	0.8336
	b	410.0627	29.5333	-0.3863	0.8287
	c	404.1812	17.1353	-0.2537	0.7372
4.13	a	2.4964	7.0417	-0.0704	0.8806
	b	0.8620	4.0307	-0.0312	0.8413
	c	-0.3571	1.3137	0.0080	0.6603

The shapes of the curves are similar for all the depths, with similar correlation coefficients for the 0-50 and 0-100 mm layers, and a slightly lower value for the 0-200 mm layer. In all cases the curves start flattening out after about 10 years, but still increasing at rather a slow rate after about 20 years. Although the data points are quite widely scattered around the fitted curve, a definite trend is visible. There is no mean C_0 value for the 0-50 mm layer but six values for the three agro-ecosystems for the 0-100 and 0-200 mm layers are available from the data of Lobe *et al.* (2001) and Du Toit *et al.* (1994). The mean C_0 value for the 0-200 mm layers is 13.7 g kg^{-1}. Using this value for y in the relevant equation provides a procedure for estimating how long it might take for complete restoration, i.e. to return to conditions as they were under native grassland. Substituting values such as 100 or 200 years for x shows that the relevant equations predict that C_0 can't be achieved. As this is illogical, the equations must be spurious, probably mainly at the top end, above about 15 years, where there are only a few data points.



(a)



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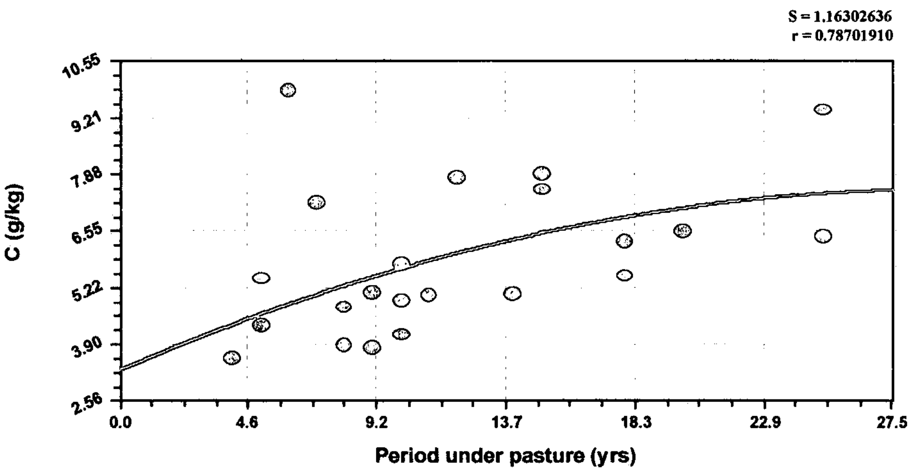


(c)

Figure 4.10 Increases in carbon content with increasing period under perennial pasture in the 0-50 mm (a), 0-100 mm (b) and 0-200mm (c) layers. Combined data for the Harrismith, Tweespruit and Kroonstad agro-ecosystems.

4.3.1.2 Relative values

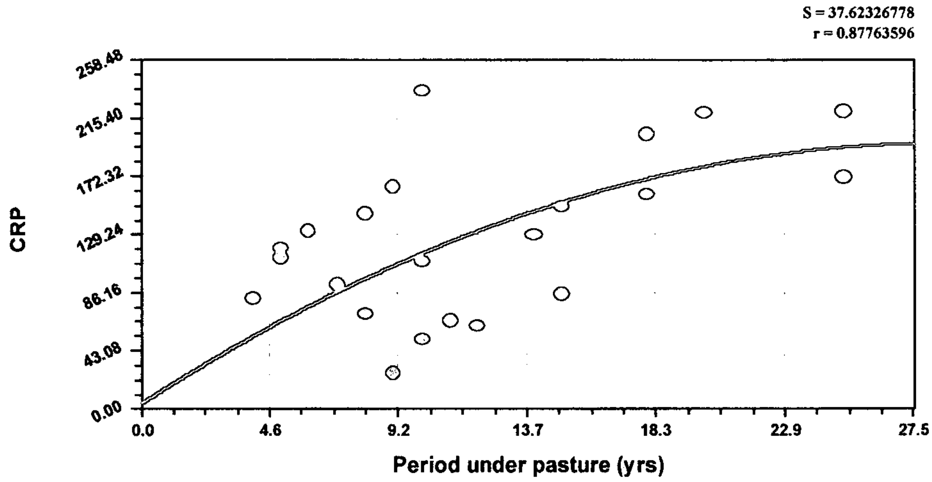
In Figure 4.11 the carbon restoration percentage, calculated as CRP = $(C_p-C_e)*100/C_e$ for each layer is plotted against the period under pasture. As the C_e values, specific for each agro-ecosystem were used in the calculations, this procedure is advantageous as it has a normalizing influence on the data. The intercept on both axes is now at zero. The shape of the curves are very similar to those in Figure 4.10. Using agro-ecosystem specific C_0 and C_e values in the CRP equation it is possible to calculate a maximum CRP value for each agro-ecosystem for each of the 0-100 and 0-200 mm layers, and a mean for the three agro-ecosystems. Results are presented in Table 4.6.

Table 4.6 Maximum CRP and NRP values for the 0-100 and 0-200 mm layers of the three agro-ecosystems. Meaning of abbreviations as defined in the beginning of the dissertation.

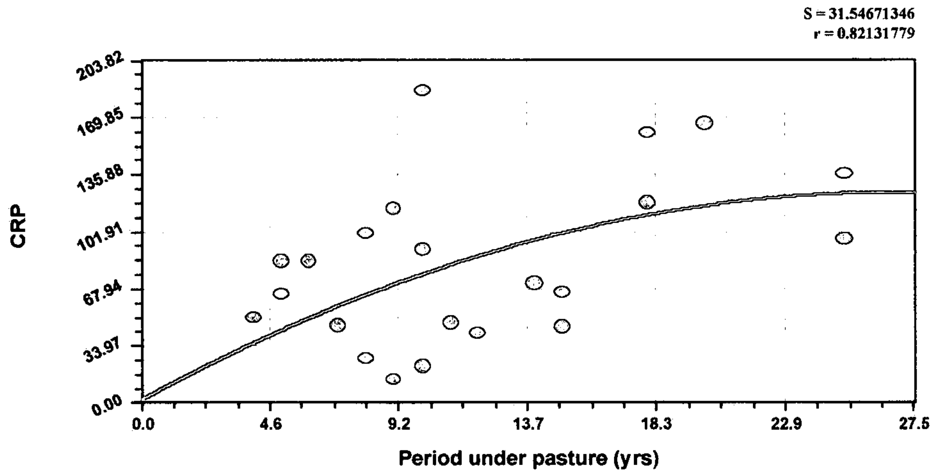
Agro-ecosystem	Maximum CRP* (%)		Maximum NRP* (%)	
	0-100 mm	0-200 mm	0-100 mm	0-200 mm
Harrismith	314	227	231	165
Tweespruit	300	205	164	136
Kroonstad	203	154	131	118
Means	272	195	175	140

* Maximum CRP and NRP calculated as $(C_0-C_e)*100/C_e$ and $(N_0-N_e)*100/N_e$, respectively

In the 0-100 and 0-200 mm layers the predicted CRP values at 25 years are 124 and 68% respectively (Figures 4.11b and 4.11c), still far short of the relevant maximum values of 272 and 195% recorded in Table 4.6. As the curves have virtually flattened out at this stage they are clearly spurious at their top end for the same reasons as those given for Figure 4.10. The fact that for the 0-200 mm layer the three CRP values around 18-20 years are all higher than the two values for 25 years supports the contention that the curve is over accentuating the flattening out tendency.



(a)



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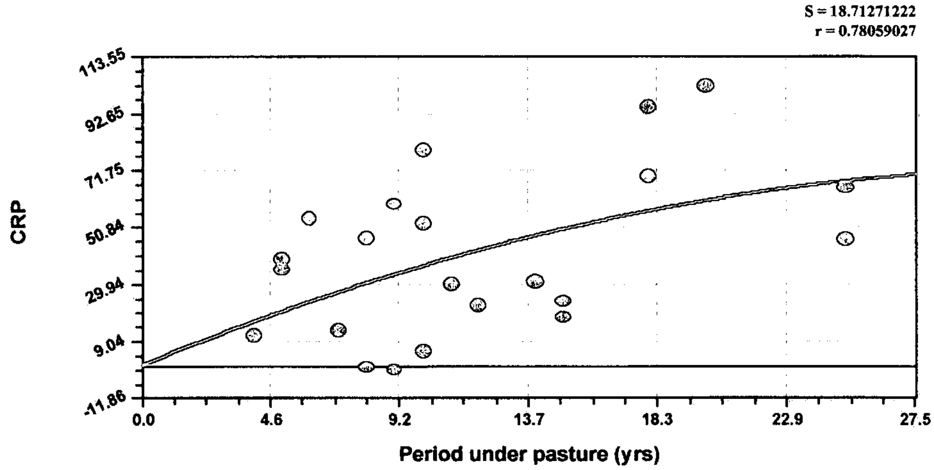


(c)

Figure 4.11 Carbon restoration percent (CRP) with increasing period under perennial pasture in the 0-50 mm (a), 0-100 mm (b) and 0-200 mm layers (c). Combined data for the Harrismith, Tweespruit and Kroonstad agro-ecosystems.

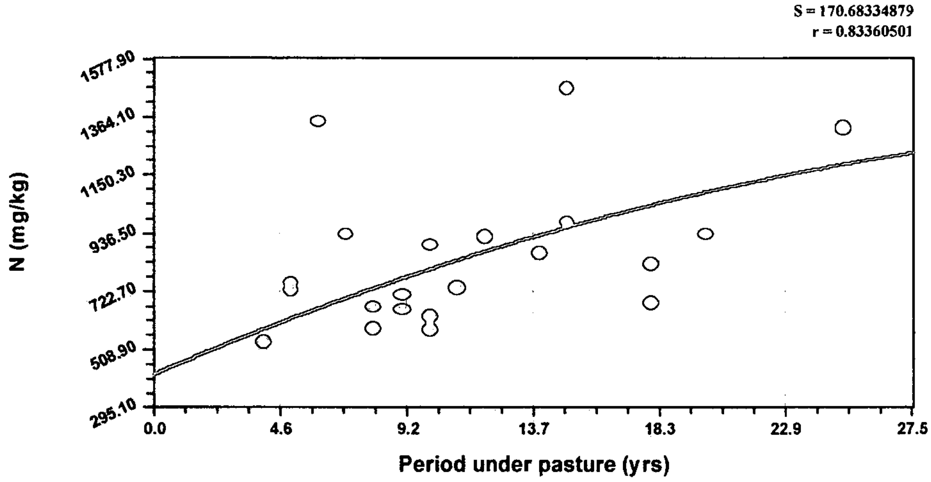
4.3.2 Total nitrogen

4.3.2.1 Absolute values

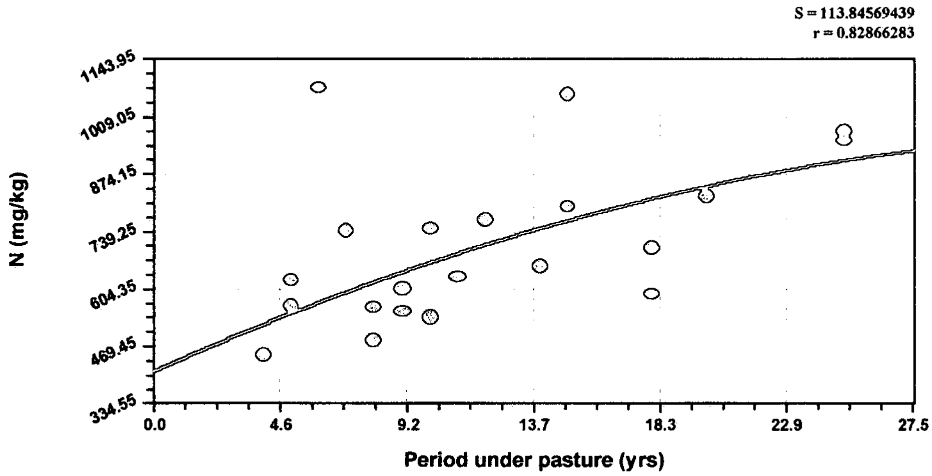
Results are presented in Figure 4.12. The curves were forced through 402 mg kg^{-1} N at 0 years, the lowest N_e value for the 0-200 mm layer of the three agro-ecosystems. The shapes and correlation coefficients of the curves are similar to those for C, with the one for the 0-200 mm layer again the flattest. As for C, it is useful to compare the maximum values on the curves for the 0-100 and 0-200 mm layers at 25 years with the respective N_0 values of 1416 and 1218 mg kg^{-1} while also taking into consideration the b and c coefficients which describe the shape of the curves. The curve predicts that it will be impossible to achieve the N content of virgin grassland however long the land is kept under perennial pasture. As this is illogical the curves must be spurious, presumably mainly at their top end where there are few data points.

4.3.2.2 Relative values

Results are presented in Figure 4.13. The nitrogen restoration percentage is calculated as NRP = $(N_p-N_e)*100/N_e$, using agro-ecosystem specific N_e values. The curves for all the layers are steeper than those for C with minimal flattening out in the curves for the 0-50 and 0-100 mm layers and no flattening out for the 0-200 mm layer at 25 years. It seems very unlikely that the latter curve can be correct. Calculating a mean maximum NRP for the 0-100 and 0-200 mm layers, as described for C, yields 175 and 140% respectively (Table 4.6). Using the relevant equations which describes the curves (Table 4.5), substituting 175 and 140% for y in the equations for Figures 4.13b and 4.13c, and solving for x by iteration makes it possible to calculate the time which the curves predict will be required for N restoration back to virgin grassland. For the 0-100 mm layer NRP reaches a maximum of 130% at about 60 years and then declines gradually. For the 0-200 mm layer it is predicted that maximum NRP will be reached at approximately 75 years.



(a)



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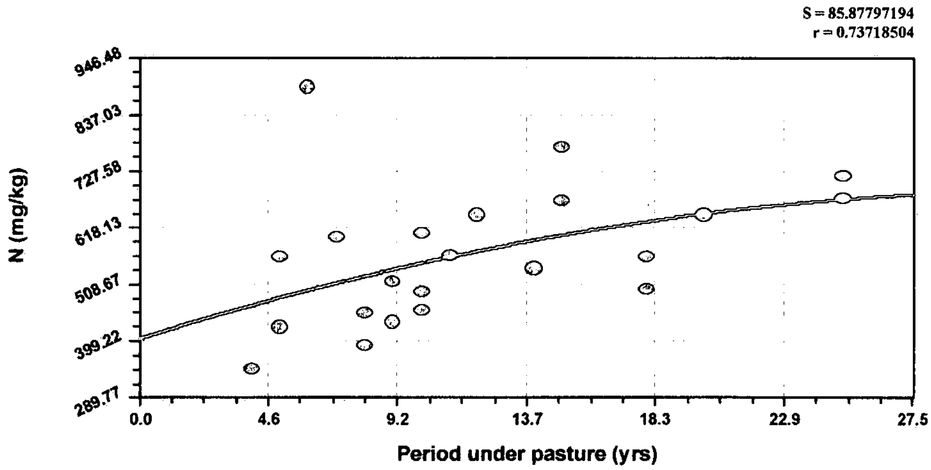
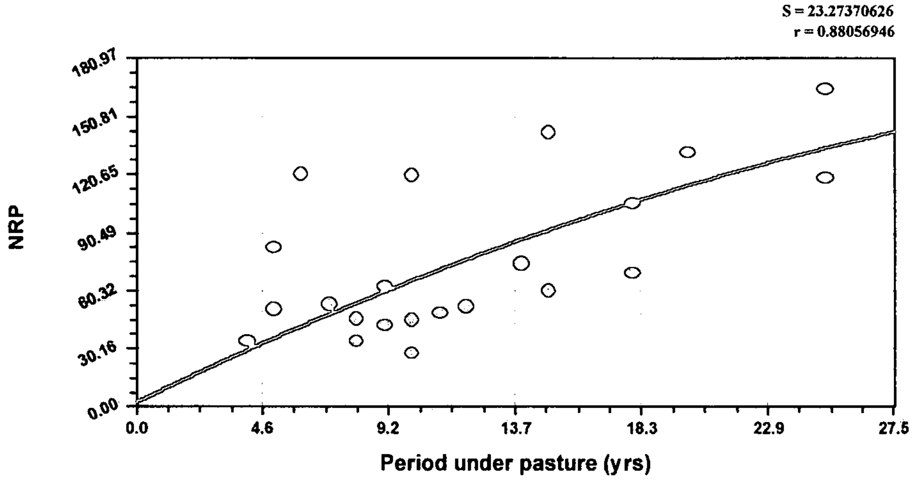
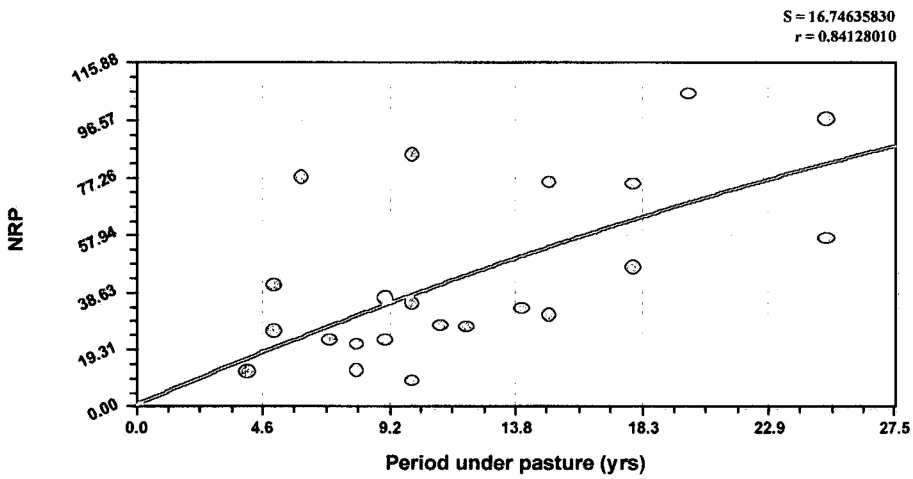


(c)

Figure 4.12 Increases in total nitrogen content with increasing period under perennial pasture in the 0-50 mm (a), 0-100 mm (b) and 0-200 mm (c) layers. Combined data for the Harrismith, Tweespruit and Kroonstad agro-ecosystems.



(a)



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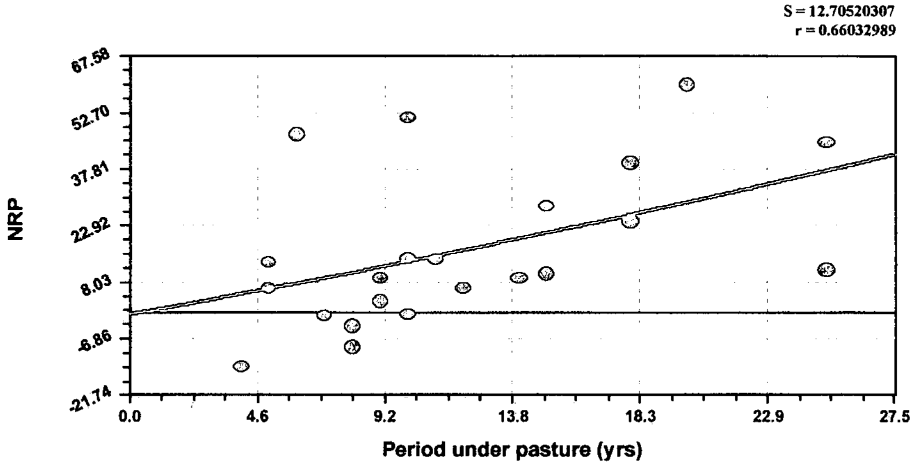

(c)

Figure 4.13 Total nitrogen restoration percent (NRP) with increasing period under perennial pasture in the 0-50 mm (a), 0-100 mm (b) and 0-200 mm (c) layers. Combined data for the Harrismith, Tweespruit and Kroonstad agro-ecosystems.

4.4 CONCLUSION

Results show that the rate of organic matter restoration at different sites varies greatly on all three agro-ecosystems, mainly because of differences in natural resource factors and management techniques. This variation makes it difficult to define in a reliable way a restoration pattern with time, and therefore to predict the time required for complete restoration back to the virgin state. The absence of measurements from pastures older than 25 years adds to this difficulty. If certain extraneous values are excluded the mean C restoration rate for the three agro-ecosystems is about two thirds of that predicted by Bruce *et al.* (1999) for the first ten years under pasture in the United States of America and Canada. The C restoration rate was highest for the Harrismith agro-ecosystem, with Kroonstad next and Tweespruit the lowest. Natural resource conditions are the most favorable at Harrismith for organic matter restoration. Poor results for Tweespruit are probably due mainly to low N fertility levels at three of the sites.

The value of sampling the old plough layer at the three depths 0-50, 50-100 and 100-200 mm has been clearly demonstrated. In this study C and N storage is shown to proceed from the top downwards, with most of the storage having occurred in the 0-50 mm layer during the first 25 years under pasture. This observation indicates that the time to complete the restoration of the 0-200 mm layer is probably going to be in excess of 75 years, since the restoration rate is expected to decline at some stage. According to Bruce *et al.* (1999) the decline in rate is expected to occur after about 10 years in the United States of America and Canada.

CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The investigation focuses on organic matter restoration under perennial pastures of different ages, ranging from 4 to 25 years, on lands which had previously been cultivated continuously for more than 20 years. The soils on the three agro-ecosystems studied, termed Harrismith, Tweespruit and Kroonstad according to the districts in which they occur, can all be described as coarse textured savannah soils of the South African highveld. The clay content range was between 7.7 and 16.6 % with an overall mean of 11.6 %. Soil samples were taken at three depths, 0-50, 50-100 and 100-200 mm, with each final sample being a composite of six subsamples to minimize within site variability. The study complements two earlier studies by Du Toit *et al.* (1994) and Lobe *et al* (2001) on organic matter degradation due to continuous cultivation on the same agro-ecosystems.

5.1 CONCLUSIONS

1. The hypothesis that the rate of organic matter restoration in cultivated land reverted to perennial pasture depends on the prevailing climate, topography, soil and the management practices is shown to be correct. A salient feature of the results is the wide variation in the rate of organic matter restoration at different sites caused by one or more of the factors named above. The variation shows clearly in Figures 4.10 to Figure 4.13, resulting in relatively low correlation coefficients and making it difficult to identify a reliable restoration pattern. It has been possible in most cases to explain the variations in terms of the prevailing factors, but there are cases where this has not been possible. An example of the latter is the massive C gain of 1.62 Mg ha^{-1} yr^{-1} of site 8 at Harrismith (Table 4.1), approximately twice as high as any other site. The following are examples of variations that can be explained; detailed explanations are given in Section 4.2:

- The C content of site 2 at Harrismith is far higher after 14 years under pasture than any other site in the three agro-ecosystems. Reasons are a high clay content of 16.6 %, which is considerably above average, and a more humid climate than the rest of the Harrismith sites. Clear evidence for the latter is presented under Section 4.2.3.

- After 8 years under pasture the N content of site 3 at Kroonstad is far higher than all other Kroonstad sites, including those 18 and 20 years old (Figure 4.8). The reason given is that the pasture consisted of a mixture of grass and lucerne, the latter providing additional N via bacterial N fixation.
- After 15 years under pasture the C content of site 6 at Harrismith is still very low, presumably due to the fact that regular burning depressed C accumulation.
- The C gains of sites 2, 3 and 4 at Tweespruit and of site 2 at Kroonstad are all below 0.15 Mg ha^{-1} yr^{-1}, compared to an average of 0.56 Mg ha^{-1} yr^{-1} for all the other sites. The cause seems to be a N deficiency since the N fertility level at all these sites is below 15.5 mg kg^{-1}, and either very little or no N fertilizer was applied.

2. A shortcoming in the study is the lack of data points for pastures that have been established for similar periods or longer than those used by Du Toit *et al.*(1994) and Lobe *et al.* (2001) for the degradation curves. They had data points up to 90 years while the oldest pasture in this study was 25 years. Having only a few data points above 20 years results in the restoration curves (Figures 4.10 to 4.13) being unreliable at their top ends, and therefore unsuitable for predicting the time needed to restore organic matter in the old plough layer to its level under virgin conditions.

3. Up to 25 years most of the C and N storage has been in the 0-50 mm layer, a little in the 50-100 mm layer and very little in the 100-200 mm layer. This finding, which is in accordance with the results of other researchers (Potter *et al.*, 1999; Sa *et al.* 2001), accentuates the importance of the sampling depth in these studies.

4. The mean C gains over all the sites in the three agro-ecosystems, excluding those where the N fertility level was considered to be too low to initiate efficient C sequestration, is 0.56 Mg ha^{-1} yr^{-1}. This is considerably lower than the approximate restoration rate of 0.8 Mg C ha^{-1} yr^{-1} for the first 10 years under perennial pasture in the United States of America and Canada suggested by Bruce *et al.* (1999). The

relatively coarse texture of the soils studied, and possibly the lower aridity indices, may account for the difference.

5. There seems to be a threshold N fertility level on old cultivated lands below which efficient C sequestration under perennial pasture does not occur. Theron & Haylett (1953) considered that this was true and designed an experiment at Pretoria to test their hypothesis. The experiment was not successful, the reason being it seems that the N content of their "degraded" land was above this proposed threshold value. The results in this investigation indicate that for the agro-ecosystems studied the threshold value of total N in the 0-200 mm layer is in the vicinity of 500 mg kg^{-1}. Assuming a mineralization rate of 3% this would produce an available N concentration of 15 mg kg^{-1}. The total N content in the 0-300 mm layer of the "degraded" soil studied by Theron & Haylett (1953), in an agro-ecosystem with a similar climate to Kroonstad, was 1050 mg kg^{-1}. This would produce an estimated available N concentration of about 32 mg kg^{-1}. It is estimated that the named threshold level of available N could be maintained by the annual addition of a fertilizer that would provide 42 kg N ha^{-1}. The estimate is based on the assumptions that the bulk density of the topsoil is 1.4 Mg m^{-3}, and that the added N would be distributed evenly throughout the 0-200 mm layer.

6. The C: N ratios tend to remain reasonably constant around an overall mean value of 10 for the 0-200 mm layer over all sites, with a range for individual sites of 7 to 15.

7. Probably the best way to compare organic matter restoration in the three agro-ecosystems is via their C gain rates in Mg ha^{-1} yr^{-1} for the 0-200 mm layer. These results are recorded in Tables 4.1, 4.2 and 4.3. Mean values are 0.63, 0.28 and 0.54 Mg ha^{-1} yr^{-1} for the Harrismith, Tweespruit and Kroonstad agro-ecosystems respectively. The abnormally low value for Tweespruit is probably due mainly to low N fertility levels at three sites that received no N fertilization. There was only one such site at Kroonstad and none at Harrismith. Higher values for Harrismith are according to expectation as the climate there is more humid and the temperatures lower than at the other two agro-ecosystems (Table 2.1). The mean value for the clay content of 13.1%

is also slightly higher for Harrismith compared to the equivalent values of 11.7 and 10.6 for Tweespruit and Kroonstad respectively. Climatic conditions at Tweespruit and Kroonstad are similar. A better C gain rate at Kroonstad may be due to the deeper soil of the Avalon form compared to the shallow Westleigh form soil at Tweespruit; the mean depths to the soft plinthic B horizon are 520 and 260 mm respectively.

5.2 RECOMMENDATIONS

1. In a study of this kind the sampling procedure is very important. The procedure used in this study, with six subsamples taken in a systematic way to give each final sample, and sampling three depths 0-50, 50-100 and 100-200 mm, has proved effective and can be recommended for future studies.

2. Information is needed from pastures that have been established for a longer time, i.e. between 25 and 100 years, in addition to those on younger pastures. Because of the wide variation in organic matter restoration at different sites, the larger the number of sample sites the better.

3. The two main factors responsible for large inter-site variations are probably natural resource characteristics and management techniques. To ensure maximum benefit from the data collected it is important that both of those aspects receive careful and detailed attention during fieldwork.

4. Valuable supplementary information could be obtained about organic matter restoration under pasture if the sites investigated in this study could be resampled in the future at intervals of a few years.

5. Knowledge regarding the shape of the organic matter restoration curve could be useful to farmers for economic reasons. Because of confounding caused by wide inter-site variation it will always be difficult with a study involving different sites to define in a reliable way the true shape of the restoration curve with time. The shape may also be ecotope specific to some extent. It would therefore be useful to start a long term

experiment involving perennial pastures established on a few benchmark ecotopes on which C and N are determined at regular intervals. The results should make it possible to define the shape of the restoration curve for a range of ecotopes in a reliable way.

6. Because of the importance of clay content in relation to organic matter restoration, it is necessary that a study of this nature be done within a defined clay content range.

7. To ensure efficient organic matter restoration on degraded lands it is advisable that the fertility level be raised to a suitable level before planting the pasture. Maintaining available N at a suitable level, well above 15 mg kg^{-1}, by regular fertilizer applications, is advisable.

8. Burning a pasture seems to have a serious detrimental effect on organic matter restoration. This practice should therefore be avoided where degraded lands are being rehabilitated.

9. Research results are available, for example Agenbach & Maree (1989), Sa, Cerri, Dick, Lal, Filho, Piccolo & Feighl (2001) and Lal (2001), which indicate that organic matter restoration can be achieved on degraded land by introducing a no-till production technique. This possibility has important economic advantages over pastures. There are however problems, for example with regard to disease and insect pests, with such a technique. It may be possible to overcome these by using suitable crop rotations. Research in this connection is recommended.

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Appendix 1: Data on particle size distribution in the 50-100 mm soil layer for every site sampled in the Harrismith, Tweespruit, and Kroonstad agro-ecosystems. Meaning of abbreviations as defined in the beginning of the dissertation.

Site*	% coSa	% meSa	% fiSa	% coSi	% fiSi	% Cl
Harrismith agro-ecosystem sites						
1	0.12	9.06	61.70	6.86	7.40	13.00
1	0.10	7.50	63.04	6.34	7.80	13.00
1	0.16	11.24	61.38	6.06	7.60	12.00
1	0.12	13.76	56.80	5.88	7.80	13.00
1	0.12	12.68	58.98	5.62	7.20	14.00
1	0.12	9.48	61.90	5.70	7.70	14.00
Mean	0.12	10.62	60.63	6.08	7.58	13.17
2	1.06	2.44	63.22	6.42	8.30	17.00
2	1.56	15.92	54.20	6.38	9.50	13.80
2	1.32	17.78	47.72	6.48	9.20	15.00
2	0.92	8.02	55.10	9.02	8.10	16.00
2	0.92	24.16	39.10	6.62	9.50	18.00
2	0.62	11.04	52.26	8.32	9.00	19.60
Mean	1.07	13.23	51.93	7.21	8.93	16.57
3	0.24	3.56	69.00	5.12	7.84	13.46
3	0.28	3.10	68.74	5.82	6.40	14.00
3	0.30	2.52	69.40	5.18	6.50	14.00
3	0.94	8.70	66.28	4.90	5.90	15.80
3	0.16	2.06	67.80	7.20	7.10	14.00
3	0.46	3.04	70.74	4.42	13.30	9.50
Mean	0.40	3.83	68.66	5.44	7.84	13.46
4	1.44	10.98	69.60	4.38	4.10	12.40
4	1.56	12.80	67.28	5.00	3.80	11.80
4	1.28	6.78	73.66	4.26	4.30	12.20
4	1.84	15.02	65.72	3.36	3.80	12.20
4	1.44	7.40	63.52	8.18	5.00	13.00
4	2.68	10.56	66.36	4.70	4.30	12.60
Mean	1.71	10.59	67.69	4.98	4.22	12.37
5	2.20	13.60	60.24	5.90	6.70	11.10
5	3.68	18.62	55.64	8.10	3.50	11.20
5	2.52	16.42	57.90	8.38	4.30	11.40
5	0.80	22.20	51.70	8.00	4.60	13.20
5	2.58	34.82	41.94	5.96	4.50	10.40
5	2.52	31.94	46.56	4.96	4.40	10.60
Mean	2.38	22.93	52.33	6.88	4.67	11.32
6	2.20	15.60	56.40	7.90	5.20	13.50
6	1.60	7.80	64.80	7.60	4.80	13.60
6	1.80	8.80	64.40	7.40	4.90	12.70
6	2.20	10.20	65.40	7.10	3.20	12.60
6	2.40	12.80	59.20	7.20	7.20	11.00
6	2.20	9.40	62.20	8.00	5.10	13.40
Mean	2.07	10.77	62.07	7.53	5.07	12.80
7	0.74	28.38	45.26	6.04	6.40	13.00

7	0.50	26.78	43.24	10.16	7.00	14.00
7	0.40	28.22	44.38	4.30	7.70	13.00
7	0.26	24.60	49.84	4.62	6.10	14.00
7	0.26	25.88	44.42	7.08	7.20	14.80
7	0.36	31.52	41.06	8.30	5.90	12.00
Mean	0.42	27.56	44.70	6.75	6.72	13.47
8	0.40	37.92	35.30	6.88	6.60	12.00
8	0.46	18.28	53.46	8.04	9.30	9.00
8	0.78	20.38	50.58	6.94	8.10	11.00
8	0.44	19.68	50.12	6.92	8.60	13.00
8	0.68	18.26	54.06	5.62	7.70	12.00
8	0.26	19.00	52.76	5.78	8.60	11.80
Mean	0.50	22.25	49.38	6.70	8.15	11.47
Tweespruit agro-ecosystem sites						
1	0.40	5.74	66.94	11.30	5.60	12.90
1	0.46	7.22	63.96	10.60	7.10	13.30
1	0.96	11.06	64.06	5.32	5.80	12.00
1	0.50	9.68	61.72	7.94	7.20	14.40
1	0.52	10.30	63.10	6.50	7.00	13.30
1	0.60	11.06	63.52	6.86	6.70	11.70
Mean	0.57	9.18	63.88	8.09	6.57	12.93
2	0.82	14.72	60.04	7.12	6.00	11.00
2	0.62	6.26	66.82	6.24	6.00	14.30
2	0.82	14.72	60.04	6.12	6.30	12.00
2	0.60	7.20	64.34	8.66	6.90	12.33
2	0.86	12.28	64.30	8.34	7.70	12.00
2	1.04	18.48	51.48	8.62	6.40	12.00
Mean	0.79	12.28	61.17	7.52	6.55	12.27
3	0.74	4.24	76.48	5.72	4.90	10.20
3	2.04	5.54	76.72	4.00	4.40	8.80
3	0.86	5.44	77.26	2.92	3.40	10.20
3	1.04	5.38	74.82	6.00	3.80	10.90
3	1.00	6.00	75.06	4.02	5.20	11.00
3	0.86	4.18	72.30	8.24	5.40	11.00
Mean	1.09	5.13	75.44	5.15	4.52	10.35
4	1.64	6.02	69.82	4.82	4.30	15.10
4	1.12	7.44	71.90	5.42	3.90	11.50
4	1.80	8.80	70.92	4.82	4.30	11.10
4	1.14	7.52	72.52	4.70	4.30	11.60
4	1.38	9.90	69.42	4.44	4.10	10.50
4	1.50	5.50	66.06	10.92	4.40	10.00
Mean	1.43	7.53	70.11	5.85	4.22	11.63
5	2.04	6.44	66.68	10.96	5.10	8.90
5	1.70	9.14	62.26	11.22	5.30	13.40
5	1.54	11.44	64.58	11.10	4.86	4.90
5	1.76	9.30	65.06	10.56	4.70	8.20
5	1.44	14.52	64.58	9.43	4.50	8.10
5	1.90	11.52	64.30	8.58	4.70	8.00

Mean	1.73	10.39	64.58	10.31	4.86	8.58
6	0.80	7.60	61.40	11.44	7.64	13.30
6	0.76	8.30	60.42	10.30	7.70	12.30
6	0.54	5.00	65.80	9.90	7.00	11.10
6	0.60	4.22	66.56	9.52	6.90	11.50
6	0.72	5.92	66.10	8.66	7.50	13.10
6	0.72	9.14	57.48	8.44	9.10	14.30
Mean	0.69	6.70	62.96	9.71	7.64	12.60
7	0.48	13.24	66.80	6.94	4.80	7.90
7	0.64	15.66	65.02	5.04	4.10	7.30
7	0.58	10.36	67.18	7.46	5.40	8.30
7	0.06	13.16	64.48	8.26	4.70	8.20
7	0.68	9.08	62.06	6.98	8.30	12.00
7	0.64	10.74	59.16	6.62	9.40	13.00
Mean	0.51	12.04	64.12	6.88	6.12	9.45
8	0.84	6.70	53.94	10.36	9.90	19.00
8	1.08	7.54	53.64	10.44	9.70	16.60
8	0.96	3.58	59.40	12.24	8.10	14.90
8	1.20	2.56	56.12	16.44	7.20	14.20
8	0.80	2.48	56.50	16.66	7.10	14.40
8	0.90	4.57	57.82	14.52	7.20	14.00
Mean	0.96	4.57	56.24	13.44	8.20	15.52
Kroonstad agro-ecosystem sites						
1	0.70	2.32	77.94	6.56	2.10	8.40
1	1.56	3.30	74.68	7.54	2.50	8.60
1	1.24	3.16	76.00	6.14	2.56	8.82
1	1.18	3.44	76.48	5.56	2.60	9.50
1	1.12	3.06	77.44	6.14	2.10	8.50
1	1.16	5.14	76.51	6.40	3.50	9.10
Mean	1.16	3.40	76.51	6.39	2.56	8.82
2	3.20	6.44	70.30	4.80	3.30	10.20
2	3.42	7.28	69.78	4.92	3.40	10.20
2	3.64	8.72	68.96	5.16	3.10	9.70
2	3.82	9.22	67.48	4.18	3.20	10.70
2	0.86	8.85	68.41	4.04	3.25	11.10
2	2.78	12.60	65.54	4.04	3.25	12.20
Mean	2.95	8.85	68.41	4.52	3.25	10.68
3	1.06	15.32	67.36	0.60	4.50	11.00
3	1.16	16.62	64.46	2.74	2.90	15.00
3	1.98	10.52	64.26	4.12	3.60	14.40
3	1.40	4.68	68.26	4.70	3.40	15.50
3	0.94	4.96	66.74	3.86	4.40	17.60
3	0.88	18.98	54.46	8.76	5.50	12.50
Mean	1.24	11.85	64.26	4.13	4.05	14.33
4	2.20	10.68	71.16	3.08	2.00	10.30
4	2.02	13.58	73.50	2.12	1.20	6.60
4	2.24	13.36	73.50	2.68	1.20	7.00
4	1.80	13.82	73.06	2.02	1.30	7.00

4	1.60	15.34	73.18	2.74	0.80	6.20
4	1.84	15.40	71.90	2.76	0.90	6.90
Mean	1.95	13.70	72.72	2.57	1.23	7.33
5	3.16	14.04	64.92	4.24	2.20	10.50
5	3.06	17.47	59.76	4.14	3.40	11.74
5	2.28	18.10	60.02	2.24	3.60	12.40
5	4.70	20.92	57.42	2.64	2.50	11.80
5	3.28	17.94	59.96	3.00	2.80	11.90
5	6.58	16.36	56.48	3.92	3.30	12.10
Mean	3.84	17.47	59.76	3.36	2.97	11.74
6	3.62	19.26	61.70	2.84	1.70	11.80
6	4.38	22.68	59.88	2.76	1.80	11.00
6	4.42	18.96	66.62	2.80	1.70	8.20
6	4.44	20.72	60.14	2.54	1.50	10.10
6	4.70	22.06	57.28	2.42	2.20	10.60
6	4.84	21.86	59.20	2.44	1.90	8.50
Mean	4.40	20.92	60.80	2.63	1.80	10.03
7	3.00	12.46	65.76	4.76	3.10	10.70
7	3.42	11.32	67.44	5.02	2.60	9.20
7	2.48	7.58	70.60	4.70	3.20	9.90
7	2.26	9.80	71.06	4.00	3.20	9.00
7	3.28	10.42	68.42	4.36	3.14	12.00
7	2.62	10.92	67.26	4.16	3.60	11.90
Mean	2.84	10.42	68.42	4.50	3.14	10.45
8	2.40	14.34	62.20	3.40	3.70	14.00
8	2.48	15.20	59.06	3.38	4.30	15.00
8	2.72	14.94	57.40	3.04	4.03	17.00
8	3.14	20.02	58.62	3.14	3.70	11.00
8	2.82	10.74	63.82	3.94	4.40	14.00
8	2.68	6.52	67.64	3.64	4.03	14.30
Mean	2.71	13.63	61.46	3.42	4.03	14.22
9	1.60	13.96	70.08	4.06	2.80	8.90
9	1.38	11.42	70.34	6.18	3.30	7.70
9	1.76	10.10	70.36	5.92	3.60	7.50
9	1.36	10.42	69.40	5.80	4.20	9.20
9	1.34	10.34	71.28	5.58	3.30	6.60
9	1.42	12.28	70.56	5.70	3.44	6.30
Mean	1.48	11.42	70.34	5.54	3.44	7.70
10	3.40	14.84	58.76	6.70	5.00	10.20
10	3.46	12.32	55.02	7.48	6.40	13.70
10	3.98	16.28	58.00	11.32	4.20	9.20
10	3.62	13.54	60.24	7.50	4.20	10.00
10	5.08	21.34	47.52	3.64	5.10	16.00
10	6.56	24.06	51.60	3.30	3.80	10.00
Mean	4.35	17.06	55.19	6.66	4.78	11.52
11	3.26	21.34	54.22	4.60	5.10	11.00
11	3.28	20.58	56.00	4.00	5.40	10.00
11	3.26	18.90	57.48	3.16	4.70	12.00

11	3.14	20.62	54.48	3.78	5.60	11.00
11	3.38	19.42	52.66	4.54	5.90	13.00
11	3.08	20.72	53.74	3.52	6.30	12.00
Mean	3.23	20.26	54.76	3.93	5.50	11.50
12	6.00	8.86	61.66	8.82	4.20	9.40
12	6.16	9.74	62.70	8.54	4.00	8.20
12	6.22	9.92	59.64	8.34	4.30	8.20
12	6.56	9.16	61.84	9.16	4.30	9.80
12	6.19	9.42	58.54	7.58	7.90	8.88
12	6.18	9.42	62.06	7.59	4.94	8.80
Mean	6.22	9.42	61.07	8.34	4.94	8.88

* At every site six replicate samples were collected for analysis.

Appendix 2: Data on exchangeable cations, cation exchange capacity, base saturation, acid saturation, and pH in the 0-200 mm soil layer for every site sampled in the Harrismith, Tweespruit, and Kroonstad agro-ecosystems. Meaning of abbreviations as defined in the beginning of the dissertation.

Site*	Ca (mg kg $^{-1}$)	K (mg kg $^{-1}$)	Mg (mg kg $^{-1}$)	Na (mg kg $^{-1}$)	CEC (soil) (cmol$_c$ kg $^{-1}$)	CEC (clay) (cmol$_c$ kg $^{-1}$)	BS (%)	AS (%)	pH (1:2.5)	
									H_2O	KCl
Harrismith agro-ecosystem sites										
1	322	144	88	13	5.13	39.46	53.9	46.1	5.30	4.10
1	312	148	82	13	4.96	38.13	54.1	45.9	5.25	4.15
1	320	130	86	11	4.78	39.86	56.4	43.6	5.19	4.08
1	306	110	82	11	4.78	36.79	53.2	46.8	5.09	3.97
1	304	114	86	12	4.26	30.44	60.6	39.4	5.14	4.06
1	322	126	88	2	4.70	33.54	56.9	43.1	5.18	4.07
Mean	314	129	85	10	4.77	36.37	55.9	44.2	5.19	4.07
2	238	28	48	11	6.70	39.39	25.5	74.5	4.61	3.86
2	228	28	48	12	4.78	34.66	34.8	65.2	4.57	3.93
2	232	34	58	12	6.70	44.64	26.6	73.4	4.56	3.82
2	204	40	48	14	6.17	38.59	25.6	74.4	4.53	3.92
2	224	44	52	11	6.70	37.20	25.6	74.4	4.58	3.9
2	266	46	54	11	6.87	35.05	28.3	71.7	4.63	3.65
Mean	232	37	51	12	6.32	38.26	27.7	72.3	4.58	3.85
3	638	118	112	25	4.61	35.45	98.4	1.7	5.52	4.43
3	670	130	118	24	4.09	29.19	100.0	0.0	5.46	4.10
3	606	160	106	27	4.87	34.78	91.2	8.8	5.47	4.34
3	696	144	126	23	5.04	31.92	99.1	0.9	5.60	4.49
3	704	196	130	26	5.83	41.62	89.6	10.4	5.56	4.38
3	708	204	128	27	5.65	59.5	92.9	7.2	5.61	4.33
Mean	670	159	120	25	5.02	38.74	98.0	2.0	5.54	4.35
4	380	180	86	18	4.61	37.17	68.5	31.6	5.18	4.02
4	264	246	70	16	4.00	33.90	65.1	34.9	5.02	3.96
4	240	230	66	17	4.17	34.21	57.8	42.2	5.04	3.98
4	252	236	82	28	4.35	35.64	61.4	38.6	5.18	4.02
4	306	222	74	20	4.35	33.44	64.5	35.5	4.95	3.91
4	284	244	66	15	4.96	39.34	53.7	46.4	4.93	3.84
Mean	288	226	74	19	4.41	35.62	61.8	38.2	5.05	3.96
5	320	44	42	11	3.65	32.90	57.8	42.2	4.81	4.10
5	224	52	36	14	4.00	35.71	40.3	59.7	4.67	3.90
5	256	40	40	12	4.17	36.61	42.4	57.6	4.62	3.92
5	302	48	44	12	4.52	34.26	45.4	54.6	4.68	3.95
5	246	60	38	13	3.91	37.63	44.9	55.1	4.76	3.97
5	678	154	94	14	4.09	38.56	100.0	0.0	4.60	3.88
Mean	338	66	49	13	4.06	35.95	57.4	42.7	4.69	3.95
6	138	54	30	11	4.61	34.14	24.4	75.6	5.78	4.90
6	556	156	86	15	4.52	33.25	87.6	12.4	5.79	4.77
6	536	136	84	10	4.35	34.23	86.8	13.2	5.76	4.72
6	424	122	70	12	4.43	35.20	69.2	30.9	5.56	4.43
6	606	156	88	13	4.70	42.69	89.9	10.1	5.72	4.83

6	630	214	98	14	4.87	36.34	94.0	6.0	5.88	4.88
Mean	482	140	76	13	4.58	35.98	75.3	24.7	5.75	4.76
7	446	32	62	13	4.52	34.78	63.8	36.2	5.11	4.13
7	386	26	62	14	4.26	30.44	60.4	39.6	5.45	4.08
7	342	36	60	12	4.17	32.11	56.4	43.6	5.65	4.03
7	260	26	58	14	4.43	31.68	43.1	56.9	4.89	3.96
7	316	56	46	24	4.78	32.31	46.2	53.8	4.96	4.05
7	258	38	46	31	4.17	34.78	45.6	54.4	4.87	4.01
Mean	335	36	56	18	4.39	32.68	52.6	47.4	5.16	4.04
8	548	132	102	23	7.22	60.15	55.8	44.2	5.30	4.48
8	672	172	112	23	6.52	72.46	74.2	25.9	5.56	4.71
8	552	160	96	22	6.09	55.34	66.8	33.2	5.40	4.44
8	410	110	92	23	5.74	44.15	55.7	44.3	5.33	4.45
8	540	138	108	22	8.61	71.74	47.1	52.9	5.15	4.24
8	430	104	90	23	5.74	48.64	56.9	43.1	5.08	4.24
Mean	525	136	100	23	7.00	59.00	59.0	41.0	5.30	4.43
Tweespruit agro-ecosystem sites										
1	488	300	78	24	4.17	32.36	95.0	5.0	5.71	4.62
1	436	230	68	23	5.13	38.57	67.0	33.0	5.70	4.63
1	556	328	86	21	4.78	39.86	92.6	7.4	5.77	4.72
1	578	306	88	23	5.91	41.06	76.2	23.8	5.73	4.67
1	562	342	88	23	5.91	44.46	76.5	23.5	5.70	4.67
1	574	296	82	23	4.87	41.62	90.6	9.4	5.78	4.75
Mean	532	300	82	23	5.13	39.66	83.0	17.0	5.73	4.68
2	836	190	102	27	4.17	37.94	100.0	0.0	6.00	4.97
2	898	174	106	23	3.65	25.54	100.0	0.0	6.04	5.21
2	894	182	94	23	5.30	44.20	100.0	0.0	6.16	5.25
2	898	168	92	20	5.57	35.22	100.0	0.0	6.13	5.14
2	974	160	124	19	5.65	47.10	100.0	0.0	6.13	5.15
2	902	146	104	23	5.65	47.10	100.0	0.0	5.97	5.11
Mean	900	170	104	23	5.00	40.00	100.0	0.0	6.07	5.14
3	606	158	64	22	5.48	53.71	100.0	0.0	6.09	5.23
3	612	170	62	23	6.09	69.17	100.0	0.0	6.11	5.14
3	676	162	68	23	4.00	39.22	100.0	0.0	6.07	5.12
3	636	164	62	21	3.48	31.91	100.0	0.0	6.04	5.10
3	636	182	64	22	4.09	37.15	100.0	0.0	6.05	5.15
3	610	154	64	22	3.48	31.62	100.0	0.0	6.11	5.24
Mean	629	165	64	22	4.44	43.80	99.3	0.7	6.08	5.16
4	942	226	104	22	6.52	43.19	95.9	4.1	6.08	5.09
4	676	228	52	7	4.43	38.56	99.9	0.1	5.82	4.90
4	682	200	54	21	3.65	32.90	100.0	0.0	5.84	4.91
4	662	184	50	21	2.96	25.49	100.0	0.0	5.66	4.85
4	666	184	50	22	4.35	41.41	99.2	0.8	5.69	5.11
4	676	196	52	22	3.83	38.26	100.0	0.0	5.72	4.93
Mean	717	203	60	19	4.29	36.64	100.0	0.0	5.80	4.97
5	838	206	70	21	4.35	48.85	100.0	0.0	5.90	5.18
5	860	190	80	23	4.61	34.39	100.0	0.0	5.88	5.17
5	758	188	66	20	4.17	44.78	100.0	0.0	5.76	4.99

5	810	212	64	22	3.91	47.72	100.0	0.0	5.85	5.06
5	752	174	62	22	4.17	51.53	100.0	0.0	5.83	5.02
5	758	172	60	23	3.65	45.65	100.0	0.0	5.90	5.19
Mean	796	190	67	22	4.14	45.49	100.0	0.0	5.85	5.1
6	606	202	80	24	5.22	39.23	82.8	17.2	5.36	4.40
6	544	200	70	30	4.78	38.88	82.5	17.5	5.30	4.69
6	582	218	74	23	5.30	47.79	78.9	21.1	5.38	4.39
6	548	180	70	35	4.35	37.81	90.5	9.5	5.39	4.38
6	632	210	78	32	5.22	39.83	86.0	14.0	5.41	4.47
6	620	218	70	23	3.39	23.72	100.0	0.0	5.36	4.42
Mean	589	205	74	28	4.71	37.88	91.5	8.5	5.37	4.46
7	544	180	44	30	2.61	33.02	100.0	0.0	5.77	4.80
7	472	150	36	27	5.13	70.28	61.6	38.4	5.53	4.65
7	534	196	38	26	3.13	37.72	100.0	0.0	5.63	4.62
7	538	164	42	29	3.39	41.36	100.0	0.0	5.69	4.84
7	562	162	44	28	3.39	28.26	100.0	0.0	5.69	4.80
7	854	182	120	23	2.96	22.74	100.0	0.0	5.66	4.67
Mean	584	172	54	27	3.44	38.90	100.0	0.0	5.66	4.73
8	792	124	112	42	6.09	32.04	88.6	11.4	5.57	4.53
8	814	138	114	33	5.48	33.00	100.0	0.0	5.43	4.41
8	840	116	116	24	5.39	36.18	100.0	0.0	5.41	4.42
8	646	106	98	23	6.26	44.09	70.6	29.4	5.06	4.41
8	694	130	88	23	5.57	38.65	83.3	16.7	5.42	4.44
8	732	140	86	20	5.22	37.27	92.5	7.5	5.51	4.53
Mean	753	126	102	28	5.67	36.87	89.8	10.2	5.4	4.46
Kroonstad agro-ecosystem sites										
1	572	408	112	43	5.57	66.25	90.3	9.7	5.89	4.46
1	502	374	94	20	4.61	53.59	94.1	5.9	5.99	4.73
1	438	308	76	20	4.52	51.38	81.8	18.2	5.64	4.86
1	514	266	86	19	4.43	46.68	91.4	8.7	5.75	4.76
1	460	274	76	21	4.26	50.13	87.5	12.5	5.74	4.78
1	498	326	89	25	4.70	51.60	88.9	11.1	5.62	4.60
Mean	497	326	89	24	4.68	53.27	89.0	11.0	5.77	4.70
2	162	196	68	26	3.48	34.10	57.2	42.8	5.55	4.29
2	402	152	56	21	4.17	40.92	70.9	29.1	5.51	4.20
2	376	152	52	22	3.91	40.34	71.5	28.5	5.43	4.16
2	384	152	52	24	4.26	39.82	66.8	33.2	5.35	4.02
2	460	152	66	21	6.09	54.84	54.8	45.3	5.42	4.19
2	454	172	64	22	5.13	42.05	65.1	34.9	5.46	4.31
Mean	373	163	60	23	4.51	42.01	64.4	35.6	5.45	4.20
3	900	340	110	23	6.70	60.87	95.4	4.6	5.92	4.82
3	818	384	112	22	6.26	41.74	97.5	2.5	5.83	4.66
3	836	348	88	26	6.09	42.27	97.2	2.8	5.94	4.92
3	820	402	88	19	5.83	37.59	100.0	0.0	5.89	4.76
3	882	396	112	21	4.09	23.22	100.0	0.0	6.01	5.15
3	782	374	92	24	4.96	39.65	100.0	0.0	5.82	4.75
Mean	840	374	100	22	5.66	40.89	100.0	0.0	5.90	4.84
4	456	146	96	23	3.39	32.93	100.0	0.0	6.19	4.59

4	438	132	88	24	3.48	52.70	96.8	3.2	6.20	4.74
4	438	132	88	21	3.65	52.17	91.8	8.2	6.18	4.77
4	422	116	82	24	3.30	47.20	96.7	3.3	6.18	4.64
4	430	116	88	23	3.39	54.70	96.7	3.3	6.22	4.72
4	470	114	92	19	3.91	56.71	89.3	10.7	6.30	4.97
Mean	442	126	89	22	4.00	49.00	96.0	4.0	6.21	4.74
5	552	156	124	19	5.04	48.03	84.8	15.2	5.31	4.26
5	704	138	166	24	5.91	37.66	90.7	9.3	5.26	4.16
5	616	186	132	24	5.30	42.78	89.8	10.2	5.23	4.21
5	660	156	148	23	5.30	44.95	94.9	5.1	5.34	4.25
5	666	154	144	28	5.65	47.50	89.3	10.7	5.39	4.32
5	686	134	138	24	5.83	48.15	86.3	13.7	5.18	4.11
Mean	647	154	142	24	5.51	44.85	89.3	10.7	5.29	4.22
6	594	160	108	21	4.78	40.53	91.4	8.6	5.36	4.40
6	486	120	74	23	4.09	37.15	84.5	15.5	5.39	4.35
6	498	108	80	21	3.65	44.54	96.5	3.5	5.35	4.60
6	560	526	320	23	4.61	45.63	100.0	0.0	5.34	4.31
6	612	148	96	21	4.70	44.30	92.3	7.8	5.45	4.47
6	610	132	92	19	4.00	47.06	100.0	0.0	5.26	4.27
Mean	560	199	128	21	4.31	43.20	100.0	0.0	5.36	4.400
7	570	126	86	21	4.43	41.45	89.8	10.2	5.78	4.58
7	538	314	78	21	4.43	48.20	95.5	4.5	5.78	4.65
7	528	290	84	24	4.43	44.80	94.4	5.6	5.72	4.71
7	552	486	320	20	4.52	50.24	100.0	0.0	5.71	4.46
7	582	288	82	20	2.00	16.67	100.0	0.0	5.61	4.43
7	550	294	84	22	2.09	17.54	100.0	0.0	5.72	4.57
Mean	553	300	122	21	3.65	36.48	100.0	0.0	5.72	4.57
8	584	238	78	19	6.61	47.21	64.5	35.5	6.73	5.70
8	578	104	78	17	8.43	56.23	46.0	54	6.77	5.88
8	584	302	82	18	9.39	55.24	47.5	52.5	6.59	5.64
8	992	326	144	21	5.91	53.75	100.0	0.0	6.36	4.88
8	703	340	164	30	6.52	46.58	100.0	0.0	6.33	5.41
8	779	109	109	26	5.74	40.13	90.5	9.5	6.31	5.28
Mean	703	237	109	22	7.10	49.86	82.3	17.8	6.52	5.47
9	294	196	64	22	1.39	19.54	100.0	0.0	5.78	5.25
9	216	256	60	20	1.13	18.84	100.0	0.0	5.61	4.49
9	202	226	52	20	1.04	13.91	100.0	0.0	5.69	4.30
9	414	84	94	4	1.13	12.29	100.0	0.0	5.57	4.68
9	212	228	58	30	1.22	18.45	100.0	0.0	5.75	4.45
9	204	250	54	20	1.13	17.94	100.0	0.0	5.71	4.54
Mean	257	207	64	19	1.17	16.83	100.0	0.0	5.69	4.62
10	482	230	114	19	1.13	11.08	100.0	0.0	5.68	4.87
10	488	262	124	20	1.13	8.25	100.0	0.0	5.64	4.67
10	436	216	114	21	2.43	26.47	100.0	0.0	5.82	4.64
10	490	406	124	20	1.22	12.17	100.0	0.0	5.74	5.14
10	898	300	316	21	1.13	7.07	100.0	0.0	5.57	4.84
10	408	248	116	21	1.13	11.30	100.0	0.0	5.59	4.53
Mean	534	277	151	20	1.36	12.72	100.0	0.0	5.67	4.78

11	380	264	84	27	1.30	11.86	100.0	0.0	5.57	4.67
11	350	298	90	24	1.39	13.91	100.0	0.0	5.56	4.51
11	438	302	92	20	1.13	9.42	100.0	0.0	5.47	4.52
11	414	268	94	20	1.13	10.28	100.0	0.0	5.42	4.51
11	516	268	92	20	1.39	10.70	100.0	0.0	5.45	4.48
11	518	316	96	26	1.30	10.87	100.0	0.0	5.54	4.52
Mean	436	286	91	23	1.27	11.17	100.0	0.0	5.50	4.54
12	1926	236	72	25	8.78	93.43	100.0	0.0	5.60	4.48
12	1540	246	70	24	11.48	139.98	78.6	21.4	5.59	4.38
12	1438	230	66	25	10.96	120.01	77.0	23	5.66	4.58
12	1716	236	82	24	10.52	107.36	94.8	5.2	5.73	4.67
12	1470	222	74	23	10.43	114.29	82.8	17.2	5.76	4.78
12	1494	244	66	24	10.43	114.24	83.9	16.1	5.79	4.70
Mean	1597	236	72	24	10.43	114.89	90.3	9.7	5.69	4.60

* At every site six replicate samples were collected for analysis.

Appendix 3: Data on organic carbon, total nitrogen and C:N ratios in 0-50, 50-100 and 100-200 mm layers for every site sampled in the Harrismith, Tweespruit and Kroonstad agro-ecosystems. Meaning of abbreviations as defined in the beginning of the dissertation.

Site*	Organic carbon (g kg^{-1})			Total nitrogen (mg kg^{-1})			C:N ratio		
	0-50 (mm)	50-100 (mm)	100-200 (mm)	0-50 (mm)	50-100 (mm)	100-200 (mm)	0-50 (mm)	50-100 (mm)	100-200 (mm)
Harrismith agro-ecosystem sites									
1	9.98	8.25	6.31	893	630	550	11.18	13.10	11.49
1	7.55	7.90	9.36	917	639	500	8.23	12.35	18.71
1	12.32	7.73	5.91	940	608	555	13.10	12.72	10.65
1	11.30	7.77	6.44	988	659	506	11.44	11.78	12.74
1	9.20	7.48	5.71	1024	572	493	8.98	13.09	11.58
1	11.49	7.34	6.11	776	586	506	14.82	12.54	12.07
Mean	10.31	7.75	6.64	923	616	518	11.29	12.60	12.87
2	24.95	11.23	9.84	1812	921	872	13.77	12.20	11.28
2	18.69	11.26	9.11	1422	889	774	13.14	12.67	11.76
2	21.05	12.84	9.51	1663	942	771	12.66	13.64	12.33
2	21.58	11.35	8.80	1748	862	809	12.34	13.17	10.88
2	20.28	10.07	9.86	1750	1075	894	11.59	9.37	11.03
2	23.41	11.68	10.29	1892	849	864	12.38	13.76	11.90
Mean	21.66	11.41	9.57	1715	923	831	12.65	12.47	11.53
3	6.15	6.29	5.27	690	614	576	8.92	10.24	9.16
3	5.63	5.78	5.82	722	604	570	7.80	10.41	10.21
3	6.34	6.21	6.12	703	612	601	9.02	10.14	10.19
3	5.58	6.71	5.75	736	628	552	7.58	10.69	10.42
3	6.65	6.79	6.49	860	634	595	7.73	10.70	10.91
3	11.87	7.00	6.43	842	705	668	14.10	9.93	9.63
Mean	7.04	6.46	5.98	759	633	594	9.19	10.35	10.09
4	11.73	5.11	5.55	863	583	497	13.59	8.76	11.16
4	13.05	6.66	5.05	841	552	451	15.52	12.06	11.19
4	13.52	5.89	5.53	1092	511	420	12.38	11.53	13.17
4	11.11	7.27	4.91	1071	565	448	10.37	12.87	10.95
4	10.62	6.47	4.99	806	542	465	13.17	11.93	10.74
4	14.00	6.96	4.90	913	569	460	15.33	12.25	10.64
Mean	12.34	6.39	5.16	931	554	457	13.39	11.57	11.31
5	17.33	4.31	4.68	1264	610	467	13.71	7.06	10.02
5	14.61	5.09	4.85	1476	677	480	9.90	7.51	10.10
5	16.56	4.26	3.70	1437	595	490	11.53	7.16	7.55
5	16.92	5.07	4.51	1511	628	548	11.19	8.06	8.22
5	15.85	7.05	4.28	1427	762	471	11.11	9.25	9.08
5	14.73	5.54	4.61	1713	667	455	8.60	8.30	10.14
Mean	16.00	5.22	4.44	1471	657	485	11.01	7.89	9.19
6	17.40	7.03	6.86	956	611	532	18.20	11.52	12.89
6	11.99	6.01	6.36	950	585	493	12.62	10.27	12.91
6	11.21	6.18	5.79	968	677	524	11.58	9.14	11.06
6	10.76	6.16	5.94	889	555	462	12.10	11.09	12.84
6	10.12	6.54	6.25	985	545	562	10.28	12.00	11.12
6	9.93	8.52	7.91	1089	754	674	9.12	11.30	11.72

Mean	11.90	6.74	6.52	973	621	541	12.32	10.89	12.09
7	22.29	8.07	5.70	925	609	408	24.11	13.26	13.96
7	17.03	9.10	5.98	1668	582	391	10.21	15.64	15.30
7	17.51	7.15	6.09	1391	586	436	12.59	12.20	13.97
7	14.91	8.18	6.07	1299	573	429	11.48	14.28	14.15
7	14.32	7.45	5.46	1373	605	377	10.43	12.30	14.49
7	18.63	7.21	7.51	1306	500	356	14.27	14.41	21.07
Mean	17.45	7.86	6.14	1327	576	400	13.85	13.68	15.49
8	10.71	9.25	8.18	1504	762	702	7.12	12.14	11.65
8	13.13	8.54	8.87	1274	817	755	10.31	10.45	11.75
8	15.91	8.85	8.09	1323	838	714	12.03	10.55	11.33
8	15.50	8.92	8.25	1253	841	751	12.37	10.60	10.98
8	17.68	9.27	7.43	1416	817	646	12.49	11.35	11.50
8	16.38	7.74	6.77	1294	779	674	12.66	9.93	10.04
Mean	14.89	8.76	7.93	1344	809	707	11.16	10.84	11.21
Tweespruit agro-ecosystem sites									
1	6.60	4.67	4.14	747	520	482	8.83	8.99	8.59
1	16.12	5.05	3.83	727	515	457	22.18	9.81	8.39
1	6.48	5.01	4.41	791	506	442	8.20	9.90	9.98
1	7.57	5.32	4.80	672	554	484	11.26	9.60	9.92
1	6.39	5.21	4.84	782	554	545	8.17	9.41	8.87
1	5.33	5.18	4.29	700	524	561	7.61	9.88	7.65
Mean	8.08	5.07	4.39	737	529	495	11.04	9.60	8.90
2	7.57	3.68	3.68	663	476	501	11.41	7.73	7.35
2	6.22	3.27	3.55	666	449	359	9.34	7.28	9.88
2	6.53	3.42	3.48	539	429	412	12.12	7.97	8.43
2	3.25	3.71	3.38	608	426	445	5.34	8.72	7.61
2	4.85	3.57	3.34	610	439	459	7.95	8.14	7.28
2	6.86	4.30	3.51	717	453	491	9.56	9.50	7.15
Mean	5.88	3.66	3.49	634	445	445	9.29	8.22	7.95
3	2.73	2.57	2.83	369	456	349	7.39	5.63	8.12
3	2.80	2.38	3.09	498	447	358	5.61	5.32	8.63
3	3.27	4.34	2.94	441	462	372	7.41	9.39	7.92
3	3.01	2.67	2.84	422	486	330	7.13	5.50	8.61
3	3.01	2.50	2.83	413	324	361	7.28	7.71	7.83
3	3.98	2.56	2.99	377	331	325	10.55	7.72	9.21
Mean	3.13	2.84	2.92	420	418	349	7.56	6.88	8.39
4	3.95	3.77	4.16	699	553	534	5.66	6.82	7.78
4	6.10	4.02	2.90	738	487	372	8.28	8.26	7.79
4	5.80	3.57	3.45	648	482	379	8.95	7.41	9.09
4	3.86	3.87	2.91	707	501	404	5.46	7.72	7.22
4	4.45	4.30	3.16	702	522	397	6.34	8.25	7.95
4	5.63	3.87	2.97	740	509	414	7.61	7.60	7.17
Mean	4.97	3.90	3.26	706	509	417	7.05	7.68	7.83
5	9.81	5.24	3.84	787	489	468	12.47	10.71	8.20
5	9.67	4.29	3.95	844	470	467	11.46	9.13	8.45
5	7.40	4.14	3.66	997	446	449	7.43	9.28	8.16
5	8.99	5.44	3.35	862	448	397	10.43	12.13	8.43

5	8.54	3.93	3.35	798	447	390	10.69	8.78	8.60
5	9.06	3.82	3.00	913	427	351	9.92	8.95	8.55
Mean	8.91	4.48	3.53	867	455	420	10.40	9.83	8.40
6	11.19	4.64	4.20	1332	632	465	8.40	7.33	9.03
6	13.73	6.24	3.48	1338	638	467	10.26	9.79	7.45
6	11.54	4.88	4.06	1302	589	492	8.86	8.29	8.24
6	13.08	5.62	3.15	1209	631	418	10.81	8.90	7.53
6	12.72	6.68	3.55	1354	672	416	9.39	9.94	8.54
6	12.96	7.08	3.64	1335	705	488	9.71	10.05	7.47
Mean	12.53	5.86	3.68	1312	645	458	9.57	9.05	8.04
7	5.68	3.09	2.54	789	481	329	7.20	6.42	7.71
7	6.79	3.47	2.74	690	657	326	9.84	5.27	8.41
7	7.33	3.45	3.55	684	395	409	10.71	8.74	8.69
7	6.08	2.73	2.60	589	425	332	10.32	6.44	7.84
7	7.52	3.42	3.05	626	369	336	12.01	9.26	9.08
7	6.39	3.03	2.69	606	398	334	10.54	7.60	8.06
Mean	6.63	3.20	2.86	664	454	344	10.10	7.29	8.30
8	9.08	4.80	6.95	910	476	697	9.98	10.09	9.98
8	7.92	4.85	4.32	815	532	511	9.72	9.11	8.45
8	8.28	4.68	4.09	768	505	468	10.77	9.27	8.73
8	8.49	4.59	3.61	681	505	432	12.48	9.09	8.36
8	8.61	3.84	3.75	654	505	436	13.17	7.61	8.59
8	7.36	4.47	3.97	674	469	439	10.92	9.53	9.06
Mean	8.29	4.54	4.45	750	499	497	11.17	9.12	8.86
Kroonstad agro-ecosystem sites									
1	12.46	7.60	4.91	1150	705	495	10.84	10.78	9.92
1	7.97	5.97	4.33	778	657	461	10.24	9.08	9.39
1	11.75	8.07	4.85	1035	785	496	11.35	10.28	9.77
1	9.15	6.76	4.52	833	660	451	10.98	10.24	10.02
1	9.08	6.01	4.24	775	703	424	11.71	8.54	9.99
1	11.52	7.09	4.15	1014	809	447	11.35	8.76	9.29
Mean	10.32	6.92	4.50	931	720	462	11.08	9.61	9.73
2	3.29	3.01	2.74	436	328	286	7.56	9.16	9.59
2	3.69	2.57	2.86	430	339	265	8.60	7.58	10.78
2	4.38	2.82	2.73	426	327	262	10.28	8.61	10.40
2	4.33	2.69	2.68	421	327	274	10.29	8.20	9.77
2	4.05	2.92	2.78	416	347	310	9.73	8.42	8.95
2	5.8	3.87	2.92	446	435	260	12.99	8.89	11.22
Mean	4.26	2.98	2.78	429	351	276	9.91	8.48	10.12
3	7.88	7.72	3.22	866	853	625	9.09	9.05	5.15
3	8.02	8.25	3.48	867	857	574	9.25	9.63	6.06
3	7.57	8.18	2.57	909	848	603	8.32	9.65	4.26
3	7.05	7.23	2.16	870	829	506	8.11	8.73	4.27
3	8.02	7.65	3.00	868	816	662	9.24	9.37	4.52
3	6.84	7.35	2.47	830	777	575	8.23	9.46	4.29
Mean	7.56	7.73	2.81	868	830	591	8.71	9.31	4.76
4	6.84	3.93	2.42	681	397	242	10.04	9.88	9.98
4	5.99	3.74	2.24	498	346	270	12.03	10.81	8.28

4	6.25	3.77	2.31	538	376	238	11.62	10.03	9.69
4	5.23	3.17	2.39	492	335	222	10.63	9.45	10.81
4	6.44	4.69	2.29	579	389	237	11.11	12.08	9.68
4	4.52	3.73	2.37	444	333	221	10.19	11.19	10.73
Mean	5.88	3.84	2.34	539	363	238	10.94	10.57	9.86
5	6.53	5.96	3.65	577	501	331	11.31	11.90	11.01
5	6.70	5.05	3.48	582	493	386	11.51	10.25	9.00
5	6.55	6.34	3.74	584	513	384	11.23	12.36	9.74
5	7.40	5.77	3.97	557	525	381	13.29	10.99	10.43
5	7.74	5.63	3.85	634	511	409	12.19	11.01	9.41
5	5.56	4.90	3.42	579	453	353	9.60	10.80	9.70
Mean	6.75	5.61	3.68	586	499	374	11.52	11.22	9.88
6	8.47	5.20	3.17	685	486	316	12.36	10.71	10.04
6	4.85	4.49	2.79	774	349	287	6.27	12.86	9.72
6	4.83	4.40	2.75	733	402	281	6.59	10.94	9.79
6	7.74	4.92	2.61	758	392	289	10.21	12.53	9.05
6	4.50	5.46	2.44	733	389	268	6.13	14.04	9.09
6	11.96	4.99	2.80	716	386	274	16.71	12.94	10.22
Mean	7.06	4.91	2.76	733	401	286	9.71	12.34	9.65
7	6.43	5.12	3.42	662	469	334	9.71	10.93	10.23
7	14.21	5.27	3.30	662	455	332	21.45	11.59	9.93
7	8.02	5.25	3.27	624	436	314	12.86	12.04	10.40
7	8.44	6.50	3.40	706	461	340	11.96	14.11	10.00
7	7.78	5.51	3.35	652	483	309	11.94	11.41	10.81
7	6.60	4.47	3.20	607	403	318	10.87	11.09	10.07
Mean	8.58	5.35	3.32	652	451	325	13.13	11.86	10.24
8	8.02	5.76	1.80	715	497	398	11.21	11.59	4.53
8	11.54	7.96	2.51	933	644	529	12.37	12.35	4.74
8	14.02	9.67	2.67	1183	547	515	11.85	17.68	5.18
8	10.78	7.32	2.45	853	723	421	12.65	10.12	5.83
8	10.66	7.33	2.76	885	613	482	12.04	11.95	5.72
8	9.91	7.59	2.12	758	601	466	13.07	12.64	4.56
Mean	10.82	7.61	2.38	888	604	469	12.20	12.72	5.09
9	8.42	4.92	3.07	612	420	299	13.75	11.71	10.25
9	6.60	5.10	2.89	555	359	260	11.88	14.21	11.12
9	9.44	4.88	2.98	561	393	302	16.81	12.44	9.86
9	7.83	5.81	3.21	758	414	297	10.33	14.03	10.81
9	7.33	5.07	3.20	536	358	307	13.68	14.18	10.44
9	7.90	4.39	2.97	500	372	281	15.79	11.81	10.55
Mean	7.92	5.03	3.05	587	386	291	13.71	13.06	10.50
10	9.91	6.99	4.30	925	553	387	10.71	12.64	11.10
10	9.79	6.05	3.88	736	497	391	13.30	12.19	9.93
10	10.62	6.49	3.94	914	505	379	11.61	12.84	10.40
10	11.30	7.73	3.92	959	692	439	11.79	11.17	8.93
10	10.05	8.27	5.32	796	689	526	12.62	12.01	10.12
10	7.31	6.36	3.87	622	550	390	11.75	11.55	9.94
Mean	9.83	6.98	4.20	825	581	419	11.96	12.07	10.07
11	6.34	5.57	3.72	695	469	358	9.13	11.88	10.39

11	8.73	5.56	3.75	634	442	358	13.76	12.56	10.48
11	8.80	5.71	3.85	670	497	397	13.13	11.49	9.72
11	8.54	6.18	4.29	678	542	457	12.59	11.41	9.37
11	9.13	5.60	4.17	689	497	422	13.25	11.27	9.88
11	8.59	6.34	3.47	717	579	445	11.97	10.94	7.81
Mean	8.36	5.83	3.88	681	504	406	12.30	11.59	9.61
12	5.44	4.58	0.96	506	404	364	10.75	11.33	2.63
12	5.14	4.29	0.91	469	375	328	10.94	11.44	2.78
12	5.89	4.65	0.95	512	405	347	11.51	11.47	2.75
12	5.68	4.88	0.96	560	434	338	10.13	11.25	2.84
12	6.36	4.67	0.97	563	418	351	11.30	11.18	2.75
12	5.09	4.62	0.97	470	411	332	10.83	11.24	2.92
Mean	5.60	4.62	0.95	513	408	343	10.91	11.32	2.78

* At every site six replicate samples were collected for analysis.